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A Design Procedure for Tapped-Delay-Line Compression Filters

by

Harry S. Hewitt

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Technical Report No. 1965-1
Prepared under
Department of the Army Contract DA 28-043-AMC-00149(E)

SYSTEMS TECHNIQUES LABORATORY
STANFORD ELECTRONICS LABORATORIES
STANFORD UNIVERSITY · STANFORD, CALIFORNIA

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A DESIGN PROCEDURE FOR TAPPED-DELAY-LINE COMPRESSION FILTERS

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ABSTRACT

A compression-filter design is described which utilizes 76 broadband taps spaced nonuniformly along a delay line. Also described is a computer program, written in FORTRAN II language, which can be used to calculate the individual tap positions and weightings for a maximum-response peak-to-sidelobe ratio. This program is quite general in that it can be used to develop an optimum (in terms of response peak-to-sidelobe ratio) compression filter for an arbitrary filter excitation-amplitude function, up to 100 taps, and any time delay-bandwidth product within the limitations of the computer storage capacity.

Computations made using the computer program resulted in a compression filter matched to an excitation which changed frequency linearly with time over an octave bandwidth and which had a time-bandwidth product of 50. The response of this filter was a compressed pulse with a peak-to-sidelobe ratio of over 100. In addition, the filter proved to be less sensitive to scan-rate errors than a continuously dispersive filter with the same compression characteristics.

Experimental results were obtained on a 76-tap compression filter designed to operate in the 1- to 2-Gc frequency range. The performance of this filter tends to confirm the validity of the technique and provides an encouraging basis for future work.

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SYMBOLS

$A(t)$	filter-excitation envelope function
$A(t-\tau_n)$	filter-excitation envelope function delayed by τ_n seconds
B_n	constant weighting factor which determines the attenuation of the n^{th} tap
ΔB	perturbation increment for B
d	distance (in.)
$e(t)$	filter-excitation function
m	total number of taps
n	number of an individual tap, counting from the input end of the filter
$r(t)$	filter-response function
$r_n(t)$	individual tap-response function
t	time variable (sec)
ϵ_r	dielectric constant relative to that of free space
τ_n	time delay encountered by a signal in traveling from the first tap to the n^{th} tap, then back to the first tap along the parallel transmission line (sec)
$\Delta\tau$	perturbation increment for τ (sec)
ϕ	phase constant (cycles)
$\phi(t)$	phase function of time (cycles)
$\omega(t)$	frequency function of time (radians/sec)

ACKNOWLEDGMENT

The author is indebted to Dr. W. R. Kincheloe, Jr. for his advice and encouragement during the course of this work, as well as for suggesting the original problem. The U.S. Army Electronics Laboratories at Fort Monmouth, N.J. provided the support for this project.

I. INTRODUCTION

A. THE PULSE-COMPRESSION FILTER

A pulse-compression filter is a device for compressing the energy of a frequency-modulated pulse into a shorter pulse [Refs. 1 and 2]. Thus a lossless compression filter might shorten a 1-μsec, 1-v (rms) FM pulse into one of the same energy with a duration of 10 nsec and an amplitude of 10 v. The degree of shortening of the pulse is known as the compression factor (or ratio) and would be 100 for the above filter. The compression filter operates by selectively delaying various portions of the pulse to be compressed so that energy at the beginning of the pulse is delayed just long enough to emerge from the filter simultaneously with energy from the beginning of the pulse.

This selective delay of the frequency-modulated pulse can be done in several ways. One method is to use a network whose delay varies with frequency. Another is to use bandpass filters to separate the pulse energy into discrete parts according to frequency and then to recombine the parts through the use of suitable delays into a shorter pulse of larger amplitude. This report is concerned with a third method--a tapped delay line with broadband filters on each tap.

B. THE TAPPED DELAY LINE WITH BROADBAND TAPS

The tapped-delay-line compression filter is, in its simplest form, a delay line with provision for extracting portions of the signal energy from various parts of the line and adding these portions together at the output. This is illustrated schematically in Fig. 1. By adjusting the positions of the taps, the various portions of signal energy can be made to add in phase at some particular time. At times other than the instant of phase addition, some degree of phase cancellation should take place depending upon the number of taps, their relative amplitude contribution, and the characteristics of the input signal.

Figure 2 is a computer-generated plot of the response of a tapped-delay-line compression filter of ten taps to sinusoidal excitation of constant magnitude and linearly varying frequency. The ten sinusoids

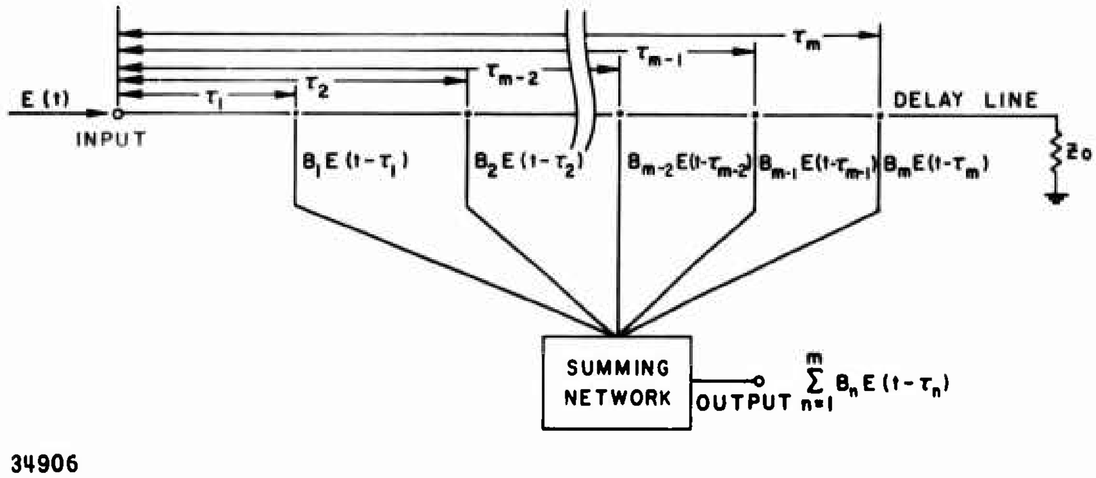

FIG. 1. TAPPED DELAY LINE WITH m TAPS.

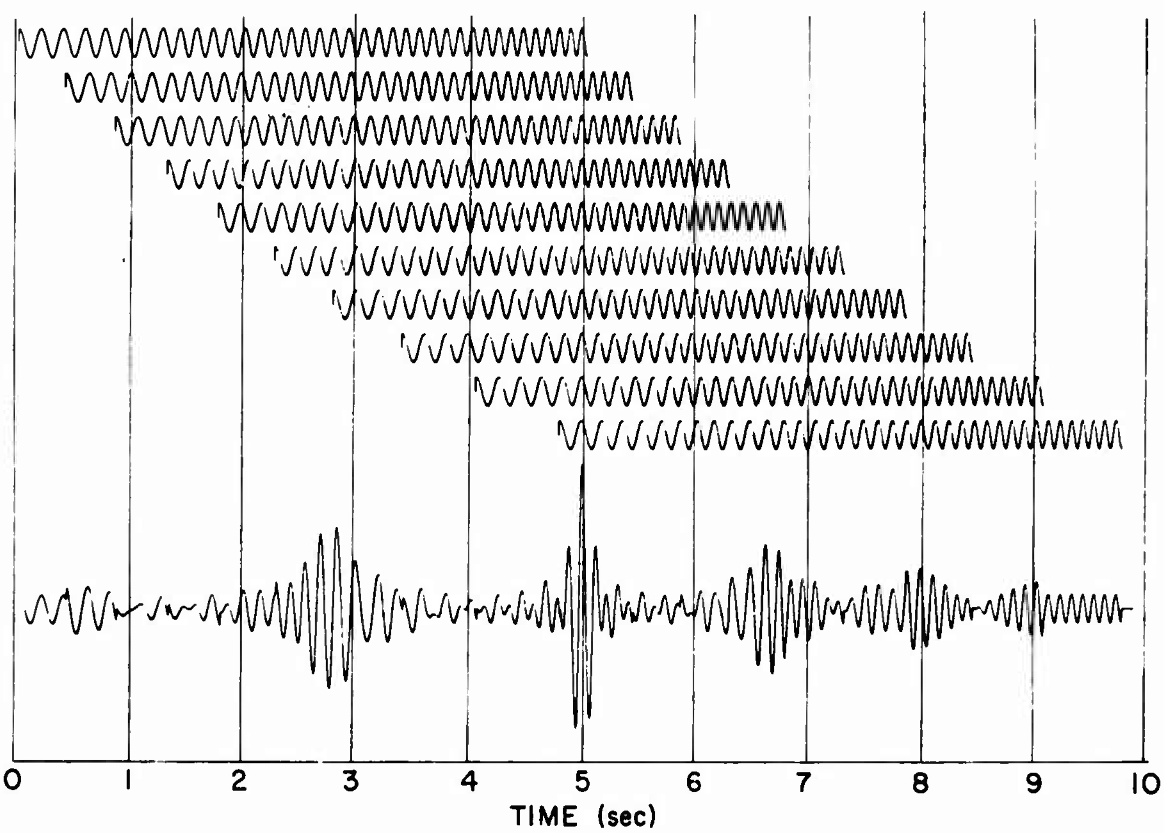

FIG. 2. TEN-TAP COMPRESSION FILTER.

representing the responses of the individual taps are shown staggered in time by amounts equal to the delays of the taps. The bottom trace is the sum of the responses of the ten taps and is seen to have a large peak at $t = 5$ sec, where the ten taps are all adding in phase. The other peaks in the bottom trace are reduced in amplitude due to the combined effects of fewer taps contributing and imperfect phase addition. These secondary peaks are analogous to grating lobes obtained by diffraction gratings and may be spaced farther apart from the main peak by increasing the number of taps.

C. GENERAL PROGRAM DESCRIPTION

The computer program presented in this report was designed to arrive at the optimum delay and attenuation of each tap in a compression filter to obtain the maximum ratio of the amplitude of the main peak to the amplitude of the signal outside the region of the main peak. This was done by repeated perturbations of the individual tap positions or amplitudes while testing for improvement in peak-to-sidelobe (PSL) ratio after each perturbation. The sequence was arranged to operate as follows:

1. The initial tap positions and amplitude weightings are read into the program as data.
2. The filter response is calculated with the initial positions and weightings.
3. The amplitude weighting of the first tap (less attenuation) is increased.
4. The filter response is calculated and the peak-to-sidelobe ratio is compared with the original value. If it is increased, the operation moves to the next tap. If it is not increased, the sign of the perturbation is changed and the test is repeated. If this change results in improvement, the tap is left in its new position and the next tap is considered. If there is no improvement the tap is returned to its original position before moving on.
5. When the last tap is reached, the final peak-to-sidelobe ratio is compared with the original value. If the improvement is less than some predetermined value, the program is terminated. Otherwise, the above sequence is repeated using delay perturbations instead of weighting perturbations.

6. The sequences of amplitude and delay perturbations are repeated alternately with the peak-to-sidelobe ratio being compared each time with the value obtained from the previous sequence. The program terminates when the increase is less than a preset value.

The program was written in FORTRAN II language for Stanford's IBM 7090 computer. The computational portion of the program should be compatible with other computer systems comparable to the 7090 in speed and memory capacity (32,000 words). Input and output formats may have to be changed to run this program on other systems; the plot routines will almost undoubtedly have to be changed since those used are unique to the Stanford computer.

The flow chart of Appendix A should provide a useful device for the reader desiring to obtain a knowledge of the mechanics of the computer program. It should be especially helpful to a programmer in changing the program language or in making any other program modifications.

D. MATHEMATICAL DESCRIPTION OF PROGRAM

In each of the computer runs the filter excitation is expressed by the following equation:

$$e(t) = A(t) \cos [2\pi(2t - 0.01t^2)] \tag{1}$$

This equation represents a signal whose frequency is changing as a linear function of time. The normalized times and frequencies used in this program were chosen for computational convenience and could, for instance, represent nanoseconds and gigacycles as well as seconds and cycles.

The response of the n^{th} tap to the above excitation is

$$r_n(t) = A(t-\tau_n)\, B_n \cos \left\{2\pi\left[2(t-\tau_n) - 0.01(t-\tau_n)^2\right]\right\} \tag{2}$$

where

τ_n = time delay to the n^{th} tap from the filter input (sec)

B_n = amplitude multiplying factor of the n^{th} tap

The response of a complete filter of m taps is the sum of the responses of the individual taps:

$$r(t) = \sum_{n=1}^{m} r_n(t) \tag{3}$$

The coefficients in the above equations were chosen to yield a time-bandwidth product of 50 over an octave bandwidth, as may be seen by taking the time derivative of the phase of Eq. (1) to obtain the frequency:

$$\omega(t) = \frac{d}{dt}\,[\phi(t)] = 2\pi(2 - 0.02t) \tag{4}$$

The frequency is 2 cps at $t = 0$ sec and will be 1 cps at $t = 50$ sec. If the values of τ_n are chosen such that the outputs of all the taps add in phase at $t = 50$ sec, then the compressed pulse will have the desired time delay-bandwidth (time-bandwidth) product of 50. The proper values of τ_n are obtained by setting $t = 50$ sec in Eq. (2) and solving for the values of τ_n which will cause the cosine argument to equal integral multiples of 2π:

$$2\pi\left[2(50-\tau_n) - 0.01(50-\tau_n)^2\right] = 2\pi k \tag{5}$$

where k is an integer. Solving for τ_k,

$$\tau_k = -50 + \sqrt{10{,}000 - 100k} \tag{6}$$

Equation (6) indicates that there are 76 values of k from 0 to 75 that can be used to calculate usable τ's from 0 to 50. If n is taken to be the tap number counting from the filter input, then $k = 75-n$ and

$$\tau_n = -50 + \sqrt{2500 + 100n} \tag{7}$$

These are the initial values of τ_n which are used in Eq. (3) and about which the perturbations are made.

Provision is made in the program to set the initial values of B_n at any desired level. The magnitudes of the perturbations may be chosen at any initial values and, if desired, the perturbations may be changed to smaller values in midprogram. This might be desirable since it allows the program to converge on a solution with fewer steps.

The function $A(t)$ in Eq. (1) represents the composite bandpass magnitude function of all elements in the rf signal path, whether the elements precede or follow the filter. In a microwave filter of octave bandwidth, the magnitude function will probably be determined predominately by external components, such as an associated TWT amplifier. Several functions are available in the program in the form of subroutines, but the main optimizing program used a parabolic shaping function which approximated the passband shape of the TWT that was used to test the prototype filter.

In all portions of the program, time was incremented in steps of 0.1 sec. This value was chosen as a compromise between computational efficiency and accuracy. The average amplitude error introduced by this increment size is about 3 percent in the sidelobes where the time samples are random relative to the peaks, and about 1 percent in the compressed pulse which is initially fixed relative to the time samples. Since improvements in peak-to-sidelobe ratios of several hundred percent were sought, it was not expected that these errors would have any significant influence on the results.

The calculation of a PSL ratio requires that the computer be able to distinguish between a peak and a sidelobe. Normally, the first envelope nulls on either side of the main peak might be chosen as the boundary between "peak" and "sidelobe." The largest peak between nulls would then be used to determine the PSL ratio. This technique was quickly determined to be impractical when preliminary filter-response plots obtained on the computer showed that clearly defined envelope nulls did not necessarily exist in the region of the main peak. In addition, the simulation of a detector increased computer running time considerably.

An alternative method of choosing the region of the main peak is possible due to the fact that the approximate location in time of this peak is known from Eq. (5). This alternative simply involves having the computer look for the sidelobes outside some fixed time interval surrounding the time chosen in Eq. (5) in order for phase addition to occur. The optimization program described here used a time interval of ±3 sec. Inspection of the computer plots of Chapter IV will show that sidelobe suppression outside this time interval was not obtained at the expense of larger peaks immediately inside the ±3 sec boundaries. It appears that the program will be insensitive to the exact locations of these boundaries if they do not fall within the body of the main pulse.

E. INFORMATION-OUTPUT TECHNIQUE

The availability of the tape-fed plotter made the amplitude-time plot a natural form of output for this program. Not only does the plot reduce the bulk and ease the interpretation of the output, but it provides the same display that one would observe on an oscilloscope of an actual filter output.

All plots were scaled to 10 sec per inch on the horizontal scale. The vertical scale was chosen such that the absolute magnitude of the compressed pulse was 4.5 in., this value being chosen so that the plot would fit onto a standard notebook page. An expanded plot with the vertical amplitude scale multiplied by 10 was provided to allow closer examination of the sidelobe structure. Calibration tick marks were provided at the side of the plot at 0.1, 0.05, 0.025, 0.0125, and 0.01 times the peak amplitude.

The printed output includes the location of each τ_n, the magnitude of each B_n, the magnitude of the main peak and its location, the magnitude of the largest sidelobe and its location, the PSL ratio, and the improvement in PSL ratio obtained by the last series of perturbations. This information is printed each time the computer finishes the series of perturbations of the m taps, thus providing an indication of the rate at which improvement is being made in the filter.

II. COMPUTATIONAL RESULTS

A. DESIGN OBJECTIVES

The computer program was applied to the design of a microwave compression filter for use with high scan-rate excitation. The desired parameters were: bandwidth = 1 Gc, center frequency = 1.5 Gc, and time-bandwidth product = 50. The desired weighting function was approximated by the following parabolic function:

$$A(t) = \begin{cases} 1 - \left(\dfrac{t-25}{35}\right)^2 & \text{for} \quad -10 \leqq t \leqq 60 \\ \\ 0 & \text{for} \quad -10 > t > 60 \end{cases} \tag{8}$$

where t is in nanoseconds. Then the desired excitation function is

$$e(t) = \begin{cases} \left[1 - \left(\dfrac{t-25}{35}\right)^2\right] \cos\,[2\pi(2t - 0.01t^2)] & \text{for} \quad -10 \leqq t \leqq 60 \\ \\ 0 & \text{for} \quad -10 > t > 60 \end{cases} \tag{9}$$

B. OPTIMIZATION PROGRAM OUTPUT DATA

1. Computer Run A

a. Initial Conditions

$$A(t-\tau_n) = \begin{cases} 1 - \left(\dfrac{t-\tau_n-25}{35}\right)^2 & \text{for} \quad -10 \leqq (t-\tau_n) \leqq 60 \\ \\ 0 & \text{for} \quad -10 > (t-\tau_n) > 60 \end{cases} \tag{10}$$

$B_n = 0.5$

$m = 76$ taps; $n = 0, 1, 2, \ldots, 74, 75$

$\tau_n = -50 + 100\sqrt{1.01 - (0.01)n}$

$\Delta B = 0.1$ (perturbation increment)

$\Delta\tau = 0.1$ (perturbation increment)

Cutoff improvement = 1 percent of PSL ratio

Time cutoff = 30 min (computer allows this value to be exceeded by 10 percent before terminating)

b. Output

Run A terminated after being unable to obtain any improvement in PSL ratio on the fourth series of perturbations of the τ's. The improvements obtained on each series are shown in Fig. 3. Total running time of the program on the 7090 computer was 24.0 min, of which 3.6 min was compile time.

Remarks: Almost all of the improvement in this filter was obtained through perturbation of the B's. In addition, the overall trend of the perturbations was to increase the values of the B's in the center of the filter while decreasing them at the ends. It was decided to rerun the program perturbing only the B's and setting an initial weighting on their magnitudes.

2. Computer Run B

a. Initial Conditions

The initial conditions for this program were the same as for run A except that $\Delta\tau$ was not used, $\Delta B = 0.05$, and the B's were as shown in Table 1.

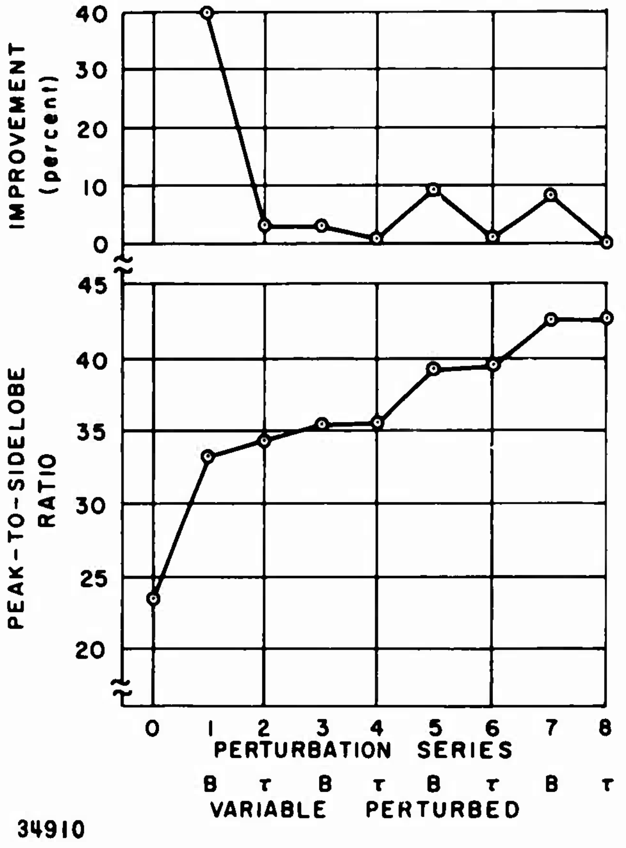

FIG. 3. PEAK-TO-SIDELOBE RATIO AND IMPROVEMENT IN PSL RATIO FOR EACH SERIES OF PERTURBATIONS OF THE 76 TAPS, COMPUTER RUN A.

TABLE 1. INITIAL VALUES OF B_n FOR COMPUTER RUN B

Tap Number	0-2 73-75	3-6 69-72	7-11 64-68	12-16 59-63	17-20 55-58	21-25 50-54	25-30 45-49	31-34 41-44	35-40
B_n	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50

b. Program Modifications

The section of Program II (see Appendix B) which is responsible for the perturbations of the τ's was removed. This is the portion of the program between the arrows on the program listing.

c. Output

This run terminated after obtaining only a 0.46-percent improvement in PSL ratio on the fifth perturbation series. The fluctuation of the improvements (Fig. 4) indicated that more running time with a smaller cutoff change percentage might be fruitful. Running time was 13 min.

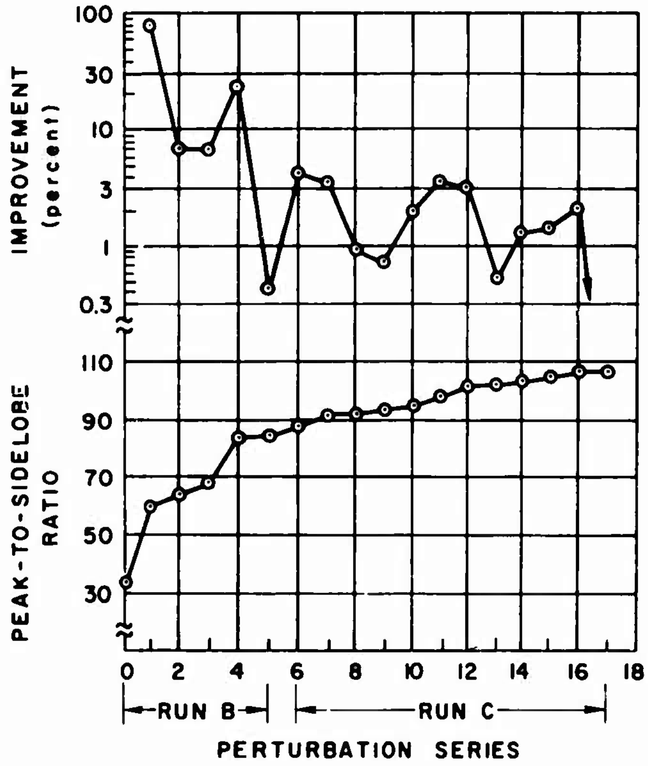

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FIG. 4. PSL RATIO AND IMPROVEMENT FOR COMPUTER RUNS B AND C.

3. Computer Run C

a. Initial Conditions

The cutoff change percentage was changed to 0.2 percent and a limit of 12 was put on the number of perturbation series allowed. The perturbation increment was changed to 0.01, and the initial B's were those arrived at in run B.

b. Output

The program terminated after 12 perturbation series were performed without encountering a change in PSL ratio less than 0.2 percent. The ratios and improvement percentages are plotted in Fig. 4, and the migrations of the weightings of the 76 taps are plotted in Fig. 5 for both runs B and C. Figures 6 and 7 are plots of $r(t)$ vs time for the final set of B's and τ's, whose values are given in Table 2. The running time was 25 min.

C. COMPUTER TESTS OF OPTIMIZED FILTER

1. Sensitivity of Filter to Random Excitation Phase

Program I was used to calculate the response of the filter derived in run C to an arbitrary phase shift in the input function. The ten phase values used were obtained from a random number table.* The function calculated is

$$r_i(t) = \sum_{n=1}^{76} A(t-\tau_n)\, B_n \cos 2\pi\left[2(t-\tau_n) - 0.01(t-\tau_n)^2 + \phi_i\right] \qquad (11)$$

where

$$A(t-\tau_n) = \begin{cases} 1 - \left(\dfrac{t-\tau_n-25}{35}\right)^2 & \text{for} \quad -10 \leq (t-\tau_n) \leq 60 \\ \\ 0 & \text{for} \quad -10 > (t-\tau_n) > 60 \end{cases}$$

B_n and τ_n are as given in Table 2, and

$\phi_1 = 0.10480$	$\phi_4 = 0.02011$	$\phi_7 = 0.69179$
$\phi_2 = 0.15011$	$\phi_5 = 0.81647$	$\phi_8 = 0.14194$
$\phi_3 = 0.01536$	$\phi_6 = 0.91646$	$\phi_9 = 0.62590$
		$\phi_{10} = 0.36207$

*C.R.C. Standard Mathematical Tables, Chemical Rubber Company, Cleveland, Ohio, 1959.

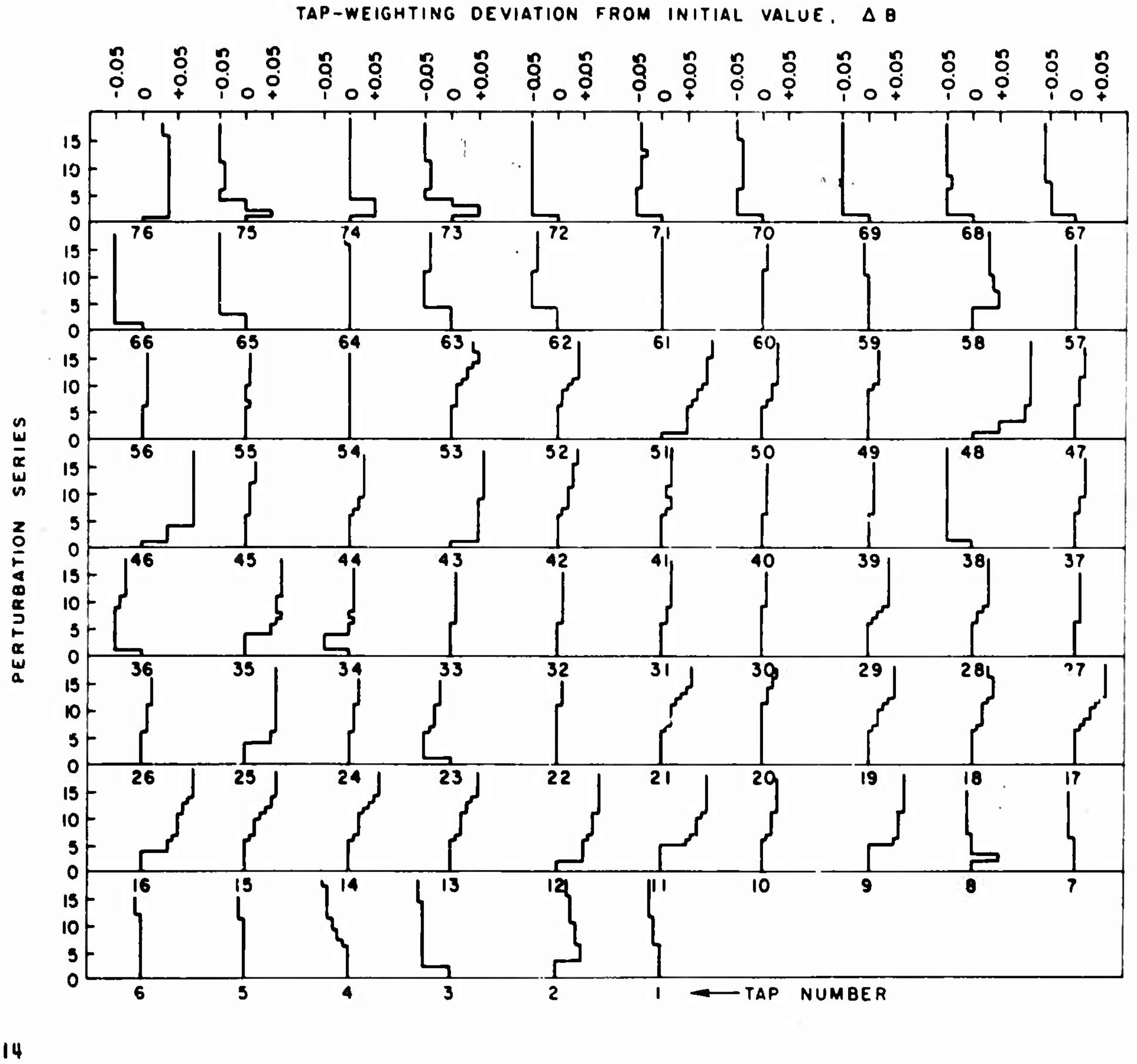

FIG. 5. TAP-WEIGHTING MIGRATIONS FOR EACH OF THE 76 TAPS DURING COMPUTER RUNS B AND C.

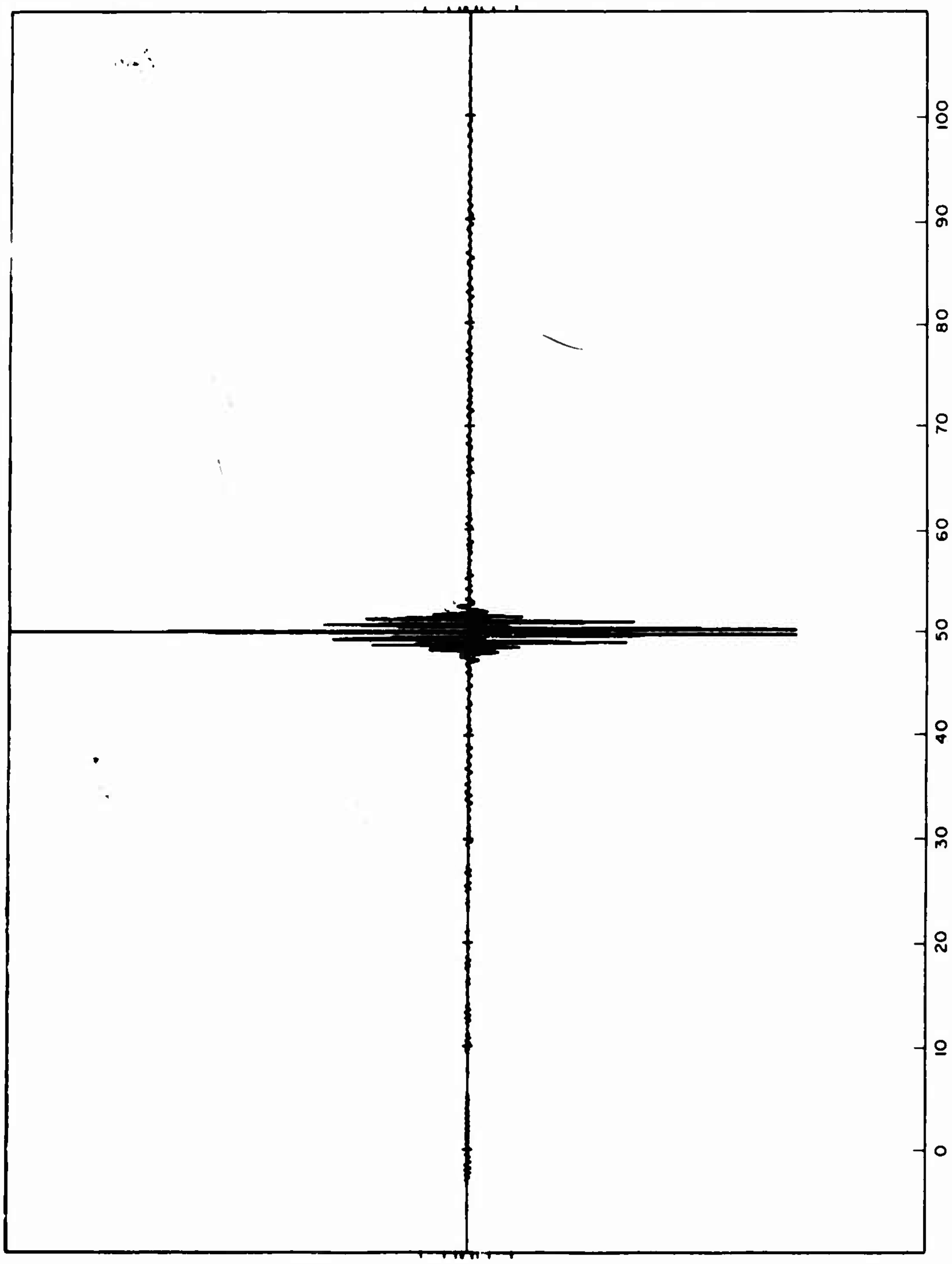

FIG. 6. OPTIMIZED FILTER RESPONSE (COMPUTED).

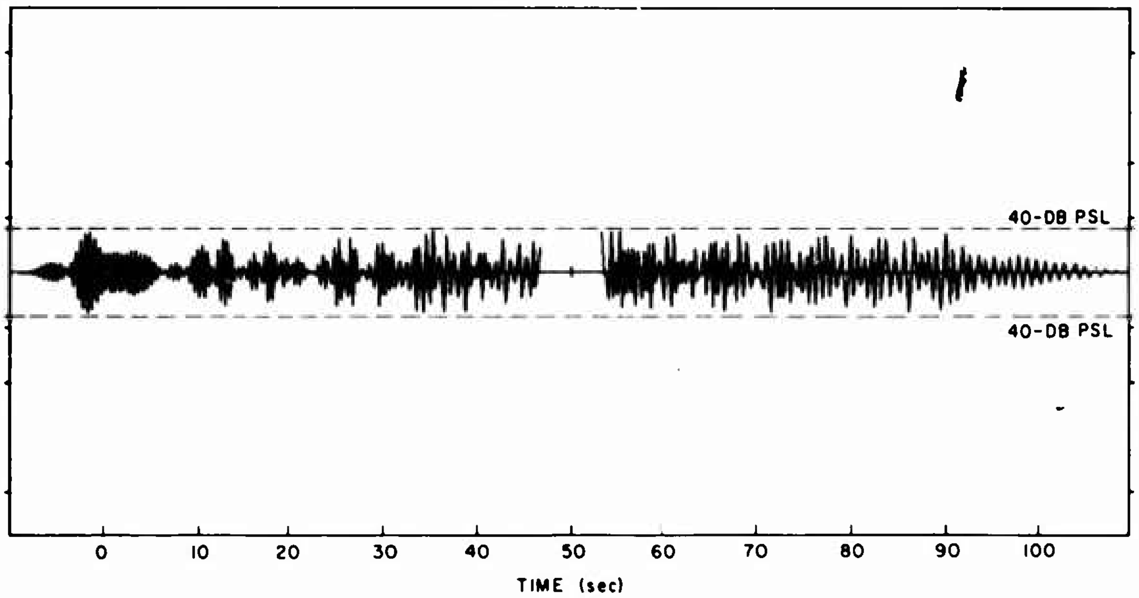

FIG. 7. OPTIMIZED FILTER RESPONSE (VERTICAL SCALE EXPANDED 10 TIMES).

The ten plots obtained were traced over each other (by hand), which resulted in the composite plot of Fig. 8.

2. Filter Response for Various Scan Rates

To test the sensitivity of the optimized filter to deviations from the design scan rate, the coefficient of the quadratic time term was changed in Subprogram ESUMI and this revised function was then used with Program I to calculate the filter response. The following coefficients were used: 0.005, 0.008, 0.0095, 0.01, 0.0105, 0.011, 0.012, 0.015, 0.02. These correspond to scan rates of 10, 16, 18, 19, 20, 21, 22, 24, 30, and 40 cycles/sec^2 respectively. The results of these tests are plotted in Fig. 9.

3. Effect of Various Excitation Function Envelopes

The four functions of Fig. 10 were chosen to test the effect on the optimized filter of a wide variation in input function shapes. The four functions used are shown beginning on page 20.

TABLE 2. VALUES OF B AND τ FOR 76-TAP FILTER WITH PSL RATIO = 107

Tap Number	B	τ (nsec)	Tap Number	B	τ (nsec)	Tap Number	B	τ (nsec)
1	0.08	0.000	26	0.37	20.711	51	0.45	36.602
2	.12	0.990	27	.41	21.414	52	.39	37.178
3	.04	1.962	28	.43	22.111	53	.39	37.750
4	.10	2.915	29	.44	22.801	54	.35	38.318
5	.14	3.852	30	.41	23.485	55	.36	28.882
6	.14	4.772	31	.42	24.162	56	.31	39.443
7	.14	5.678	32	.46	24.833	57	.30	40.000
8	.19	6.568	33	.46	25.498	58	.33	40.554
9	.27	7.446	34	.46	26.158	59	.29	41.104
10	.23	8.310	35	.52	26.811	60	.26	41.651
11	.29	9.161	36	.47	27.460	61	.25	42.195
12	.28	10.000	37	.52	28.102	62	.21	42.736
13	.30	10.828	38	.45	28.740	63	.21	43.274
14	.31	11.644	39	.51	29.372	64	.24	43.808
15	.31	12.450	40	.51	30.000	65	.15	44.340
16	.35	13.246	41	.52	30.623	66	.15	44.868
17	.31	14.031	42	.49	31.240	67	.14	45.394
18	.33	14.807	43	.51	31.853	68	.15	45.917
19	.35	15.574	44	.48	32.462	69	.15	46.436
20	.33	16.332	45	.47	33.066	70	.10	46.954
21	.36	17.082	46	.50	33.666	71	.11	47.468
22	.36	17.823	47	.42	34.261	72	.10	47.980
23	.33	18.556	48	.51	34.852	73	.10	48.489
24	.37	19.282	49	.42	35.440	74	.10	48.995
25	.41	20.000	50	.43	36.023	75	.05	49.499
						76	.14	50.000

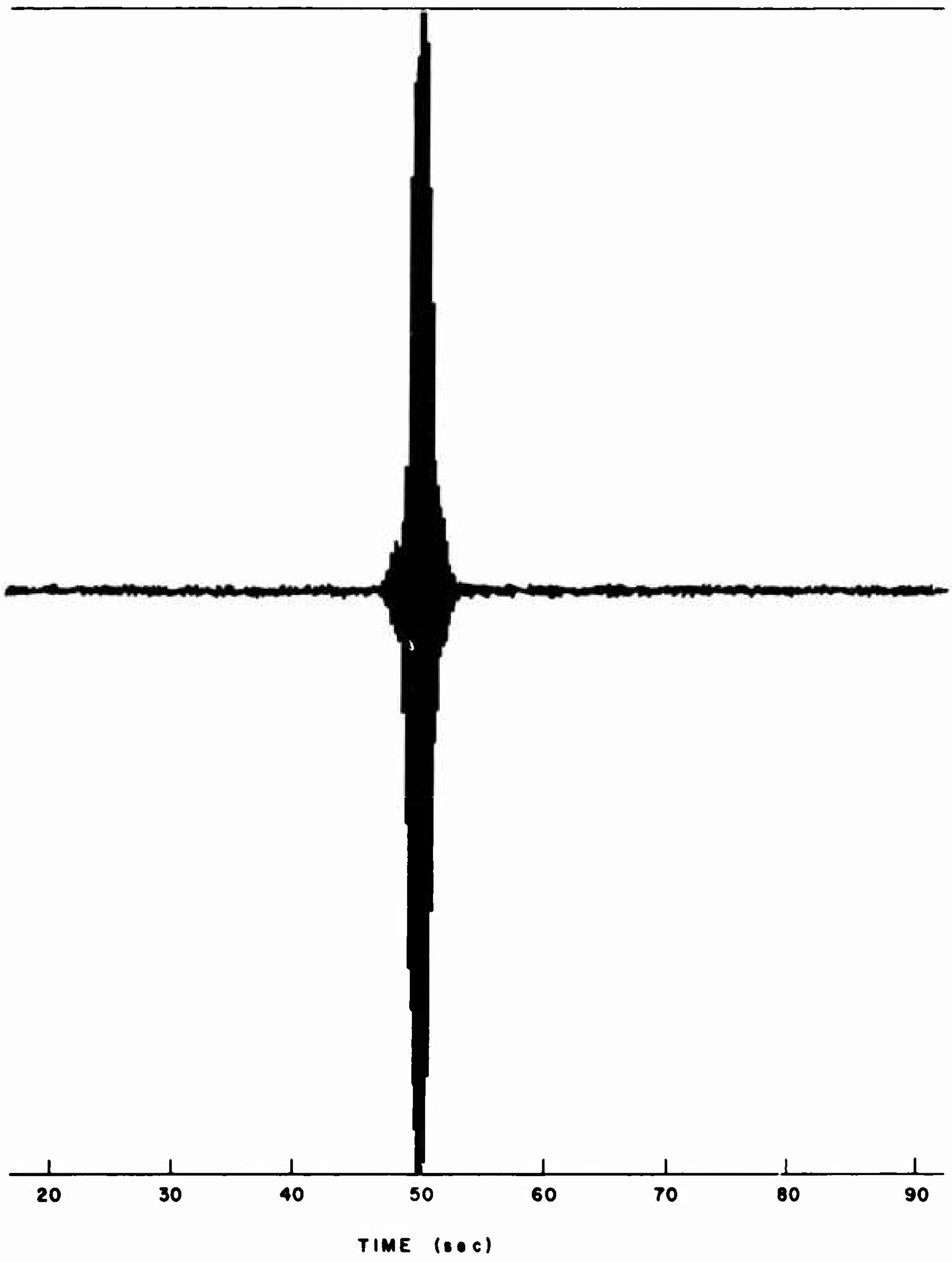

FIG. 8. COMPOSITE PLOT OF RESPONSE OF OPTIMIZED FILTER TO EXCITATION WITH RANDOM PHASE CONSTANT.

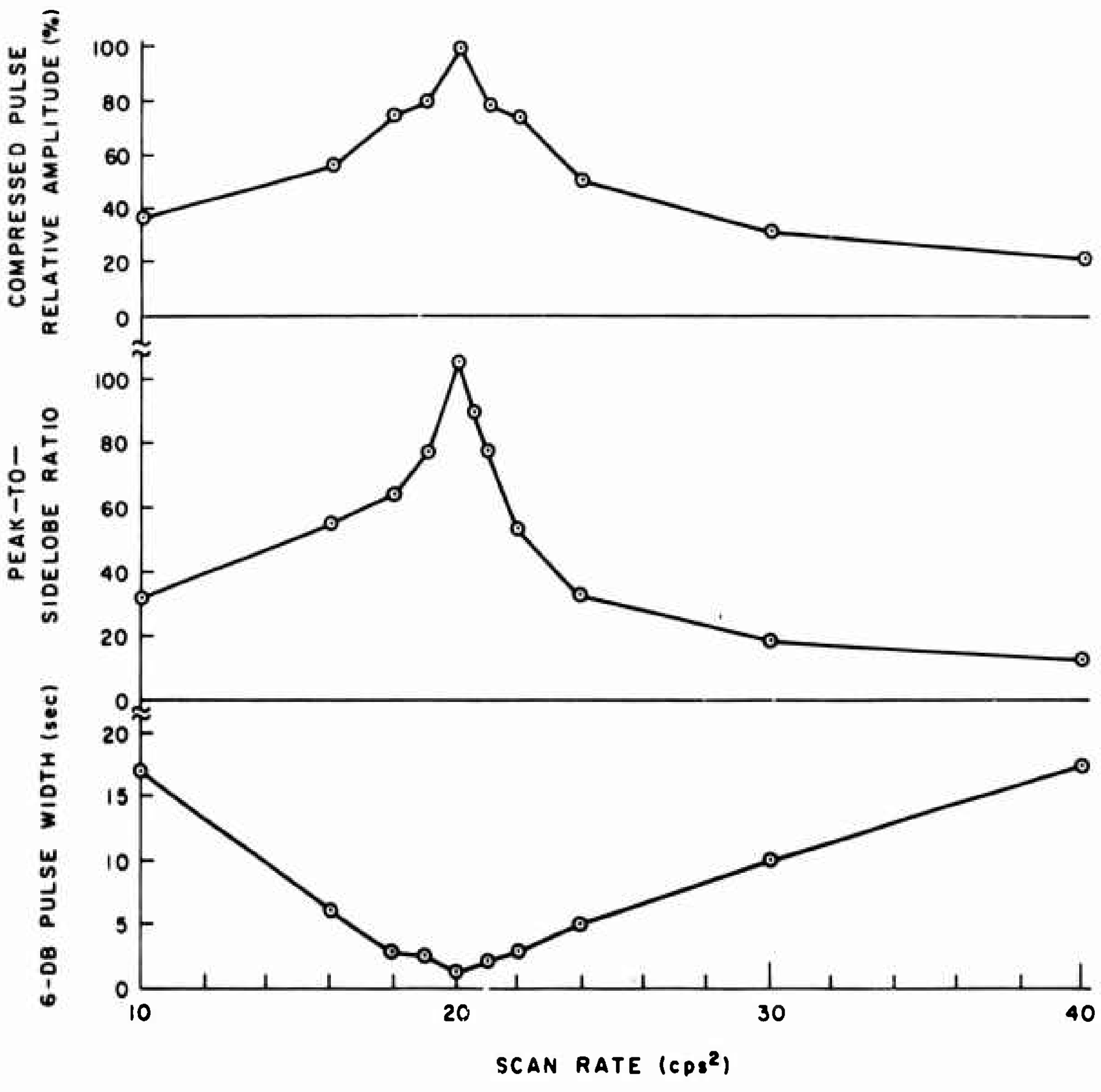

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FIG. 9. VARIATION OF COMPRESSED-PULSE PARAMETERS WITH SCAN RATE.

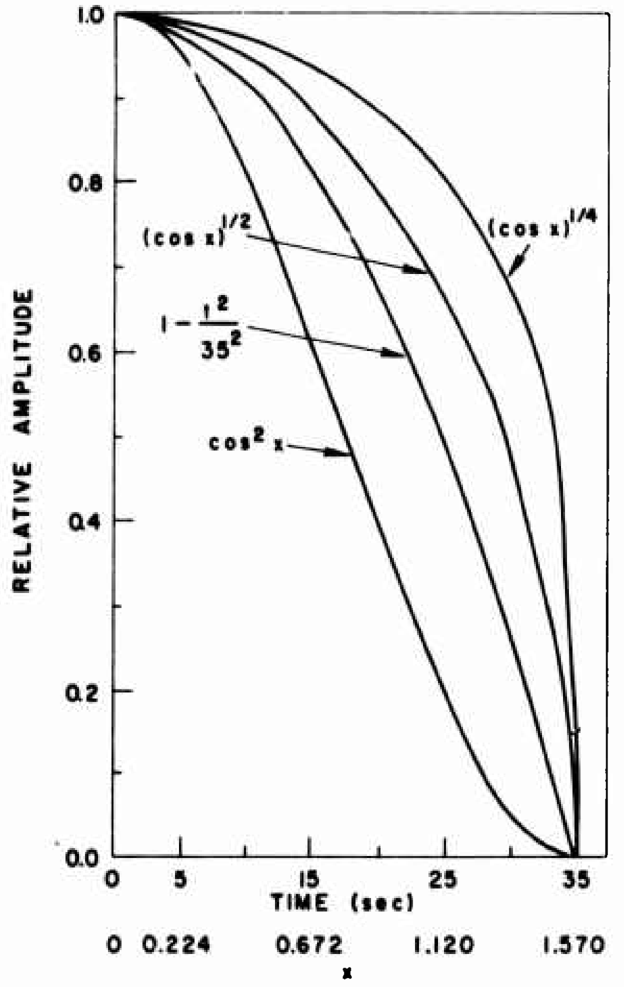

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FIG. 10. FOUR FUNCTIONS USED AS EXCITATION AMPLITUDE-WEIGHTING FUNCTION, $A(t)$.

$$A(t-\tau) = \begin{cases} 1 - \left(\dfrac{t-\tau-25}{35}\right)^2 & \text{for} \quad -10 \leq (t-\tau) \leq 60 \\ \\ 0 & \text{for} \quad -10 > (t-\tau) > 60 \end{cases} \tag{12}$$

$$A(t-\tau) = \begin{cases} \left[\cos \pi \left(\dfrac{t-\tau-25}{70}\right)\right]^{1/4} & \text{for} \quad -10 \leq (t-\tau) \leq 60 \\ \\ 0 & \text{for} \quad -10 > (t-\tau) > 60 \end{cases} \tag{13}$$

$$A(t-\tau) = \begin{cases} \left[\cos \pi \left(\dfrac{t-\tau-25}{70}\right)\right]^{1/2} & \text{for} \quad -10 \leq (t-\tau) \leq 60 \\ \\ 0 & \text{for} \quad -10 > (t-\tau) > 60 \end{cases} \tag{14}$$

$$A(t-\tau) = \begin{cases} \left[\cos \pi \left(\dfrac{t-\tau-25}{70}\right)\right]^{2} & \text{for} \quad -10 \leq (t-\tau) \leq 60 \\ \\ 0 & \text{for} \quad -10 > (t-\tau) > 60 \end{cases} \tag{15}$$

The compressed-pulse parameters resulting from these four functions are listed in Table 3.

TABLE 3. FILTER PERFORMANCE FACTORS
FOR DIFFERENT EXCITATION MAGNITUDE FUNCTIONS

Function	6-db Pulse Width (sec)	PSL Ratio	Compressed-Pulse Amplitude
$1 - \frac{t^2}{35^2}$	1.4	107	21.2
$(\cos x)^2$	1.7	100	18.5
$(\cos x)^{1/2}$	1.3	61	22.1
$(\cos x)^{1/4}$	1.3	40	22.9

4. Image Response

The sign of the scan rate was changed in Subprogram ESUMI to determine the image response of the optimized filter. The image excitation function is:

$$e(t) = A(t) \cos 2\pi(1.0t + 0.01t^2) \tag{16}$$

where $A(t)$ is given by Eq. (8). The calculated response is plotted in Fig. 11 to the same time and amplitude scale as the optimized filter response of Fig. 6. The peak magnitude of the image was 14.8 db below that of the main pulse.

D. REMARKS ON COMPUTATIONAL RESULTS

The early termination of run A was due to the inability of the program to improve the peak-to-sidelobe ratio by perturbing the τ's. As can be seen in Fig. 3, none of the four series of τ perturbations resulted in any significant improvement in the filter. Since the migrations of the B's in run A indicated a trend toward something resembling a Taylor weighting [Ref. 1], a stepped first-order approximation to this weighting was used in run B for the initial B's in order to decrease the computation time.

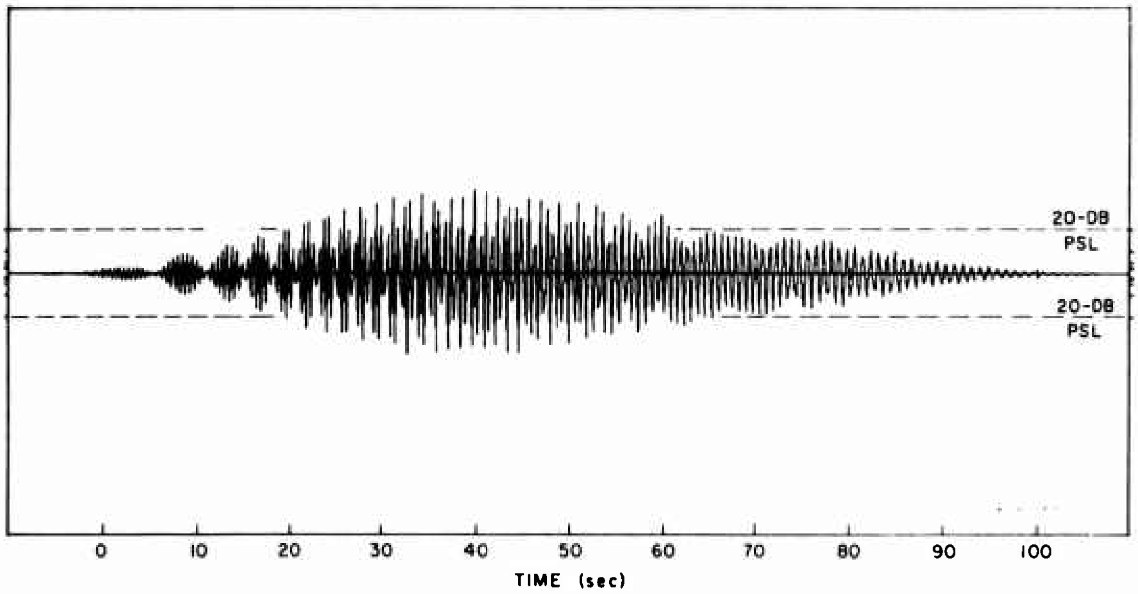


FIG. 11. RESPONSE OF OPTIMIZED FILTER TO IMAGE EXCITATION.

The fluctuations of the weightings as shown in Fig. 5 indicate that the one-at-a-time perturbation technique is not the most efficient method of deriving an optimum filter. It does, however, have the advantage of simplicity. If a new program were to be written, it would probably be better to perturb the taps in variable-size groups instead of individually.

The finally derived filter, with a PSL ratio of 107, allowed a 50-percent scan-rate error before its PSL ratio was degraded to that of the constant-weighting filter (Fig. 3). The pulse width is increased by about a factor of 10 with a 50-percent scan-rate error due to the much smaller bandwidth over which phase addition can take place.

III. EXPERIMENTAL RESULTS

As a parallel investigation to the computer synthesis of a tapped-delay-line compression filter, the realizability of such a filter at microwave frequencies was explored. The purpose of constructing this filter was to determine if phase and attenuation could be controlled to the required accuracy in a microwave device with as many as 76 taps. In accordance with the numbers used in the optimization program, the filter was designed to operate between 1 and 2 Gc, with a time-bandwidth product of 50.

A. CONSTRUCTION

The delay line was constructed from shielded stripline due to the compactness of the structure and the accessibility of the conductor for coupling purposes. It consists of two parallel strips, each 237 in. long, photoetched onto a Tellite 3B dielectric sheet 0.0625 in. thick. Another dielectric sheet of the same thickness is laid on top of the conductors, and the two dielectric sheets are then sandwiched between two aluminum ground planes to form the complete delay structure. The delay line with one ground plane and dielectric sheet removed is shown in Fig. 12. The large number of screw holes was necessary to maintain the spurious coupling level between the parallel lines at a value lower than -50 db. A drawing of the line is shown in Fig. 13.

The couplers can be resistive or reactive devices connecting the two parallel lines at the appropriate points to achieve the delays given in Table 2. Since signals on the output line can couple back into the input line and thence into the output line again through any combination of couplers, it is necessary that the couplers have at least 20-db loss to prevent spurious signals from appearing at the output in the form of sidelobes. This requirement of high coupler loss could be relaxed somewhat if directional couplers were used, but with 76 couplers the limit is still about -15 db if sufficient power is to be conserved for the last tap.

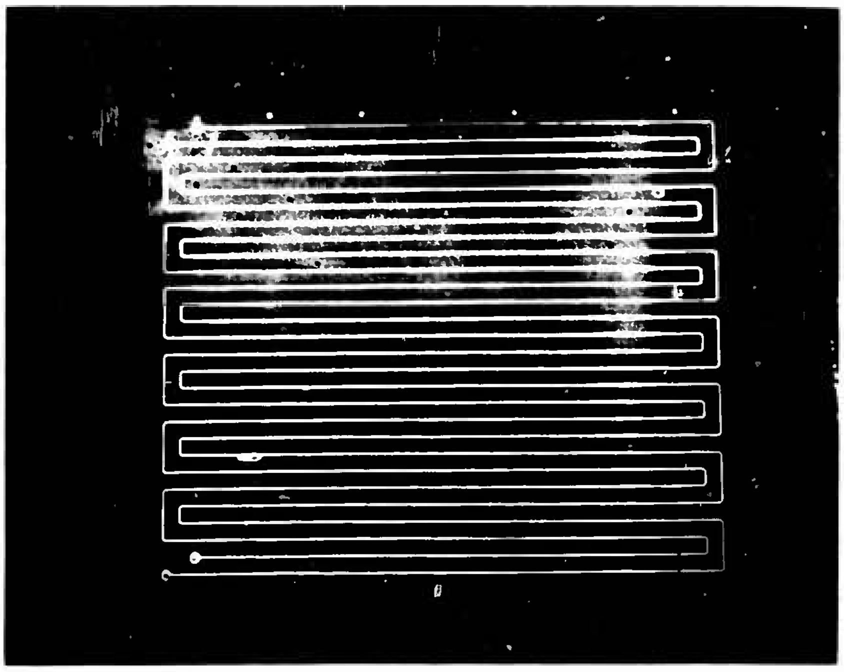


FIG. 12. PHOTOGRAPH OF PARALLEL TRANSMISSION LINES BONDED TO TELLITE 3B SUBSTRATE.

It was initially planned to use resistive taps between the two sections of the delay line. However, the fact that the resistors necessarily remove considerably more power from the input line than is delivered to the output line, makes this type of coupler unusable in this application because of the resulting high attenuation. The use of edge-coupled quarter-wavelength directional couplers [Ref. 3] was a logical consideration, but the construction and placement of 76 such couplers would involve considerable expense and time. The simpler coupler configuration actually used was intended primarily to demonstrate whether phase could be accurately controlled through 76 different signal paths simultaneously.

Figure 14 is a drawing of the coupler configuration used, and Fig. 15 is a plot of the frequency response of this coupler. It is simply a piece of No. 40 wire laid across the conductors perpendicularly and separated from them by a 0.002-in. piece of cellophane tape. Strips of 0.007-in. cellophane tape were laid between the noncoupled conductors to serve as spacers and to prevent the copper wire from being squeezed through the 0.002-in. tape.

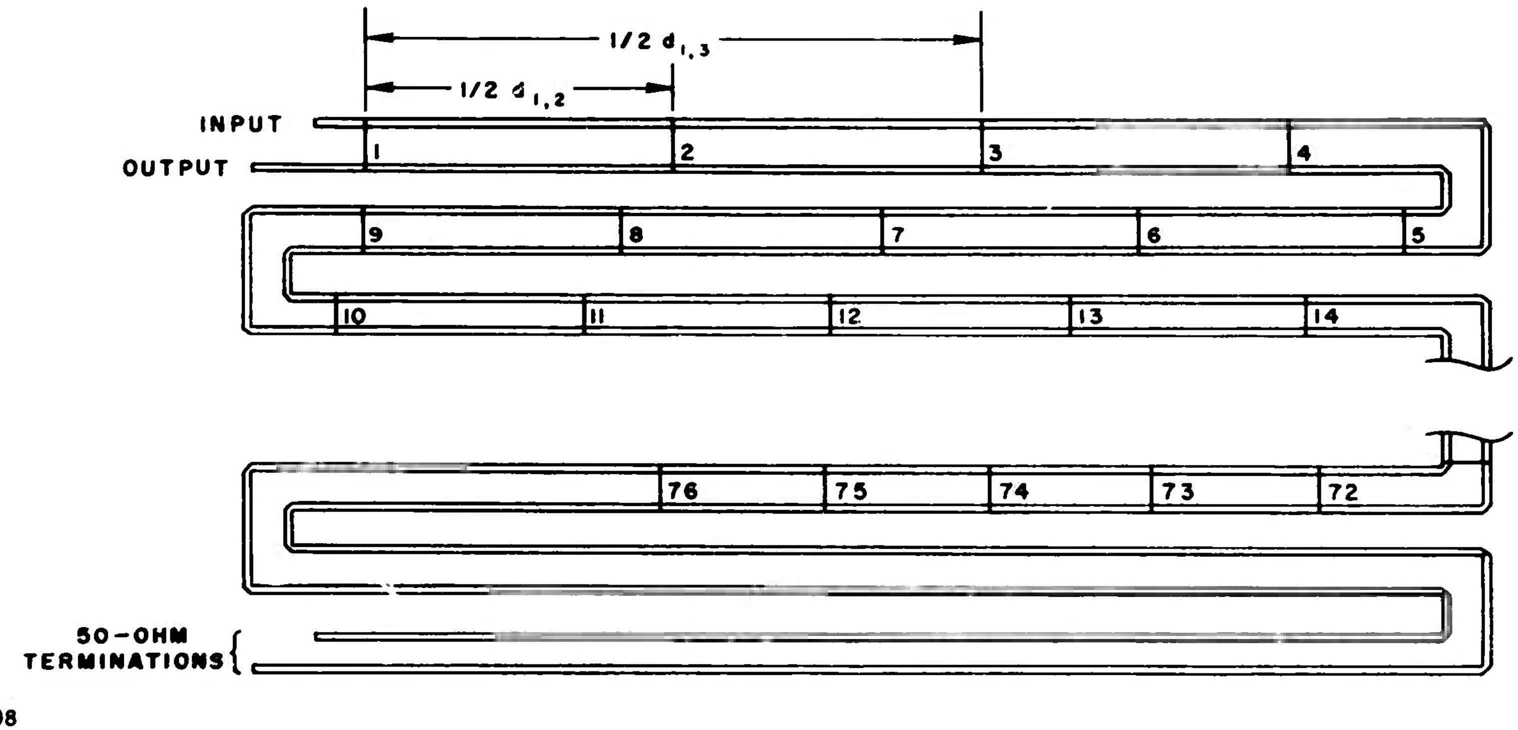


FIG. 13. PARALLEL DELAY LINES WITH 76 TAPS OF NO. 40 WIRE. Input, output, and terminations are through Gremar No. 5804 stripline to type-N transitions.

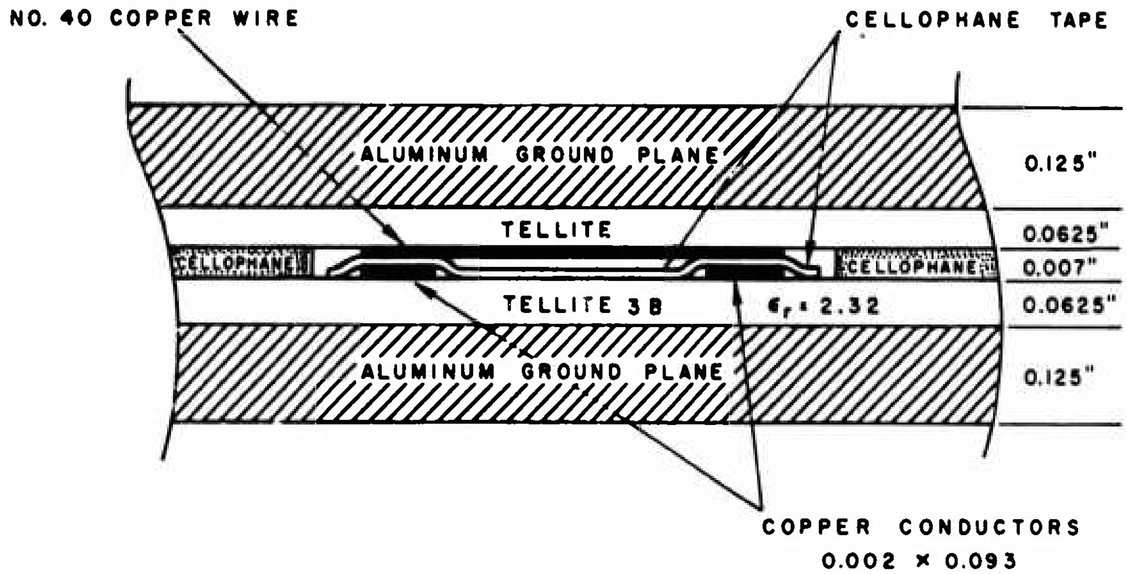


FIG. 14. CUTAWAY SIDE VIEW OF COUPLER CONFIGURATION.

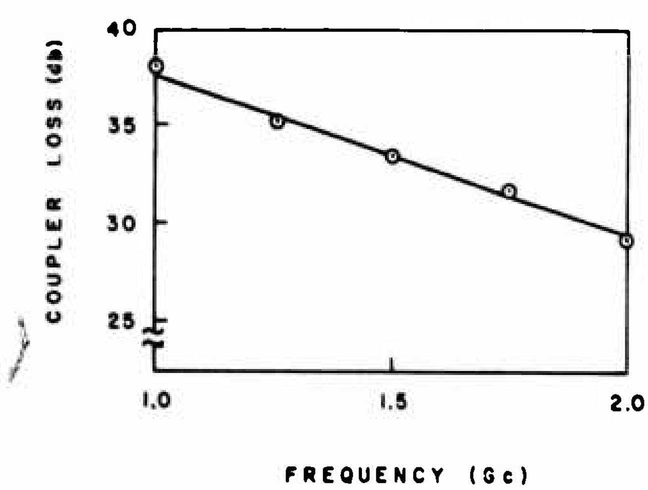


FIG. 15. FREQUENCY RESPONSE OF THE COUPLER CONFIGURATION OF FIG. 14.

The locations of the taps along the delay line were determined by the values of the τ's in Table 2. Tap 1 was used as a reference with $\tau = 0$, and the total length of delay line from tap 1 to tap n is given by:

$$d_{1,n} = (\tau_n)\left(\frac{11.803}{\sqrt{\epsilon_r}}\right) \text{ inches} \tag{17}$$

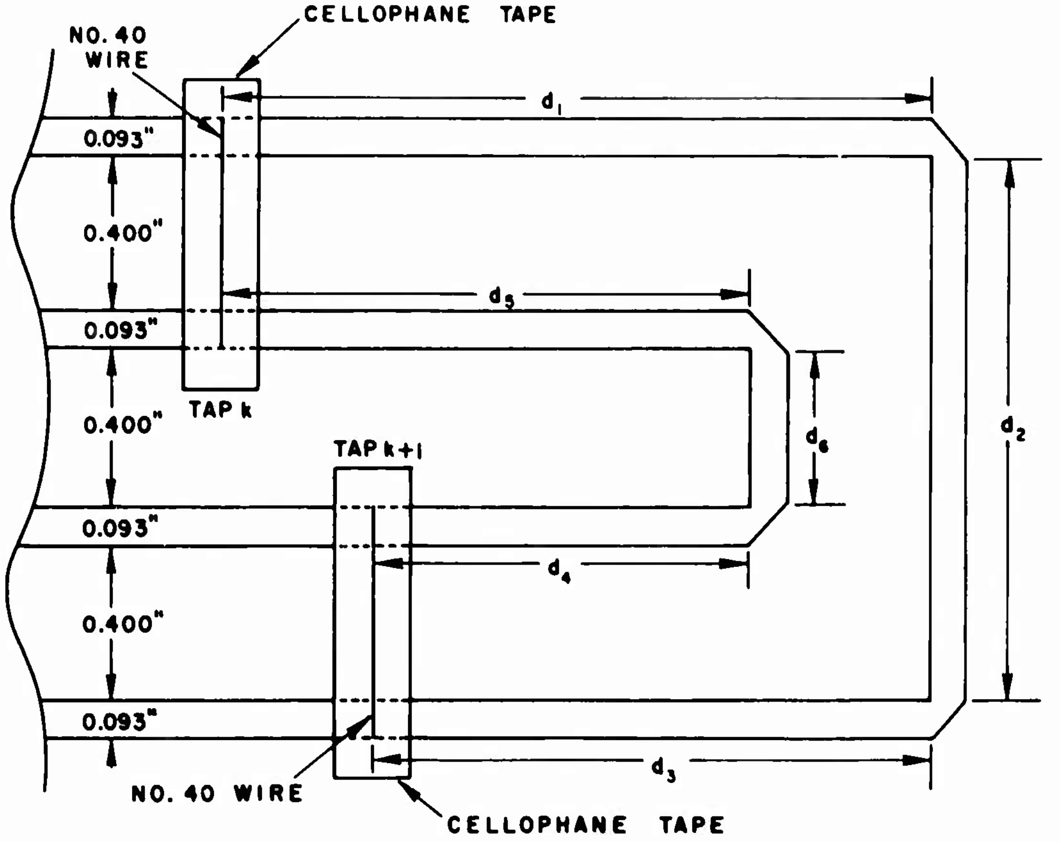
where ϵ_r is the relative dielectric constant of the substrate, (ϵ_r = 2.32 for Tellite 3B), and 11.803 in./nsec is the speed of light in vacuo. The distance $d_{1,n}$ doesn't include the length of the coupler since that is a constant value for each tap. The electrical length of the corners was determined empirically to be 0.0147 nsec or 0.114 in. for each corner. The dimensions required for a given delay are clarified in Fig. 16.

B. PERFORMANCE

The test apparatus of Fig. 17 was used to examine the compression characteristics of the prototype filter. Photographs of the filter response are shown in Figs. 18 through 22. These photographs do not necessarily represent the full capabilities of the filter because of spurious responses from the TWT's and scan-rate variations in the BWO.

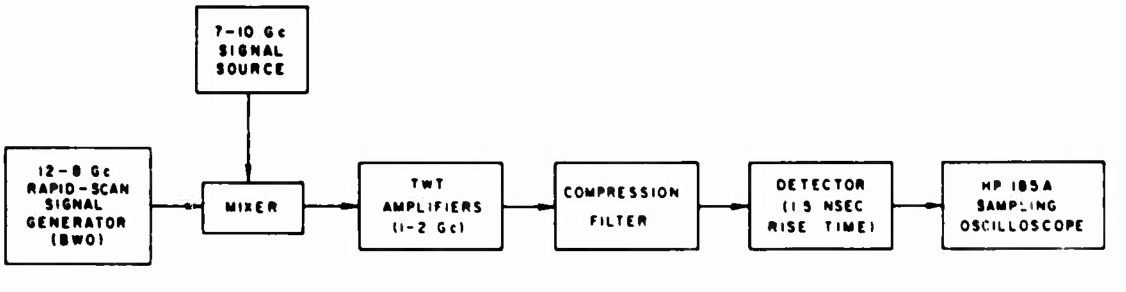
The dual-trace photograph of Fig. 18 shows the compressed and uncompressed rf envelopes in their proper time relationships. The uncompressed pulse at the filter input is attenuated by 20 db in the photograph, thus indicating a net compression loss of 20 db. From Fig. 15 the filter loss at the TWT center frequency (1300 Mc) is 34 db, which gives a compression ratio of approximately 14 db or 25 to 1. This result suggests that the phasing of the individual taps is accurate since an in-phase contribution from almost all of the taps is required to achieve a 14-db* compression ratio with the limited bandwidth of the TWT's. The magnitude of the

*The compression factor is equal to the product of the bandwidth over which in-phase contributions are obtained times the differential time delay of that bandwidth in the compression filter. This "time-bandwidth product" is explained in detail in Ref. 1.



34907

FIG. 16. DIAGRAM SHOWING METHOD OF MEASURING ELECTRICAL DISTANCE BETWEEN TWO TAPS. In general, $d_{k,k-1} = (d_1 + d_2 + d_3 + d_4 + d_5 + d_6) + 4d_7$. For the dimensions shown, $d_7 = 0.114$ in., where d_7 is the electrical distance around a corner.



34913

FIG. 17. SIGNAL FLOW DIAGRAM OF APPARATUS FOR TESTING THE 76-TAP FILTER.

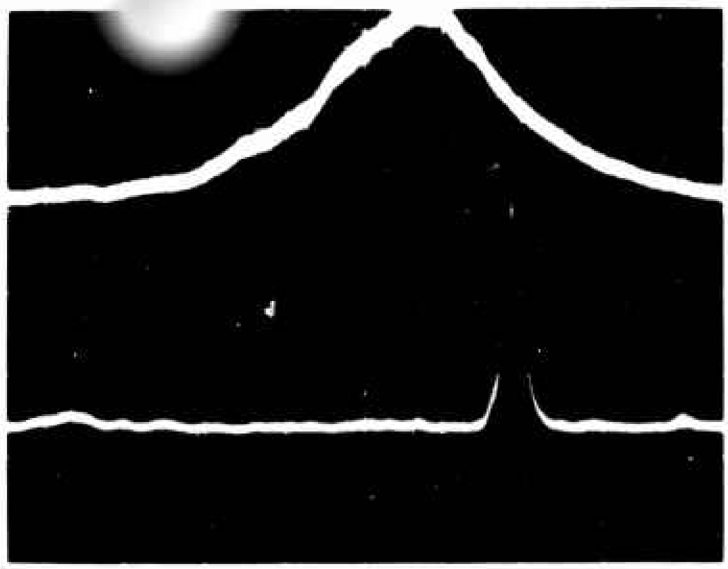


FIG. 18. DUAL-TRACE PHOTOGRAPH OF 76-TAP FILTER RESPONSE AND EXCITATION. Lower trace: compressed-pulse envelope, 10 nsec/div. Upper trace: excitation envelope, same relative time scale. Amplitude is proportional to power in both traces.

frequency response of the TWT's is the shape of the uncompressed pulse of Fig. 18, with frequency decreasing from left to right and the point directly over the compressed pulse corresponding to 1 Gc. The 10-nsec/div time scale converts to a 200-Mc/div frequency scale as a result of the 20-Mc/nsec scan rate.

The "spreading" effect of the compression filter upon a signal scanning in the wrong direction (such as an image) is shown in Fig. 19. The image energy is spread out in time to approximately twice its original duration, giving the signal-to-image ratio as the compression ratio times 2, or in this case, 14 + 3 = 17 db. This ratio is not apparent in Fig. 19 due to the fact that the sampling oscilloscope distorts signals whose durations are very short compared to the time scale.

The duration of the compressed pulse, when observed on the expanded time scale of Fig. 20, is seen to approach that of the impulse response of the TWT's (Fig. 21). For comparison purposes, it should be noted that the compressed pulse is a detected envelope, while the actual rf cycles of the TWT impulse response are shown. Also, the compressed-pulse amplitude is proportional to power, while the impulse-response amplitude is proportional to voltage.

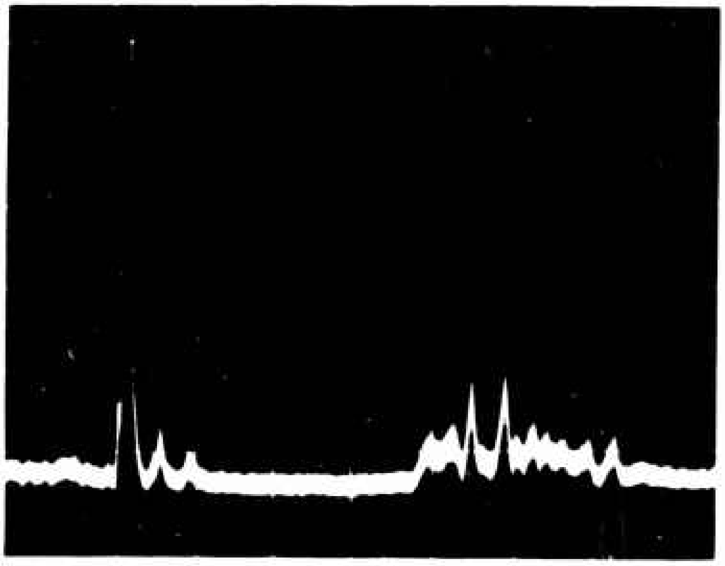


FIG. 19. COMPRESSED PULSE AND IMAGE RESPONSE, 25 NSEC/DIV. Amplitude is proportional to power.

FIG. 20. COMPRESSED-PULSE ENVELOPE, 2 NSEC/DIV. Amplitude is proportional to power.

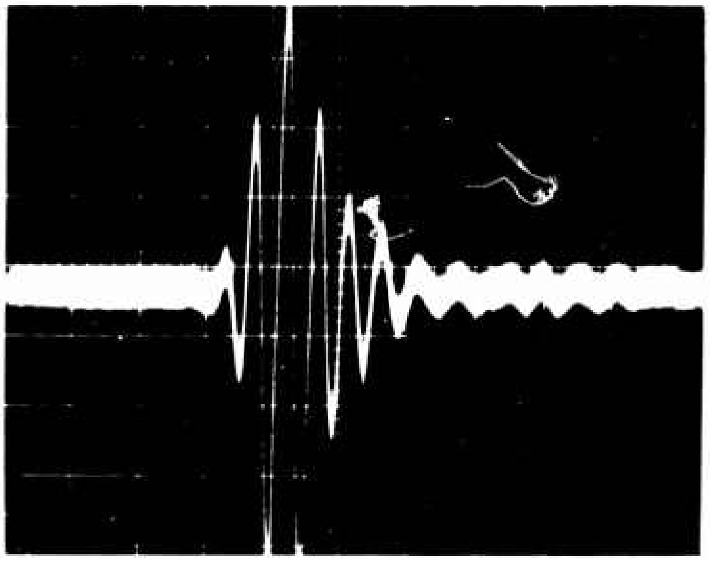


FIG. 21. IMPULSE RESPONSE OF TWT AMPLIFIERS USED IN COMPRESSION SYSTEM, 2 NSEC/DIV.

The last photograph, Fig. 22, illustrates the sidelobes present along the baseline of the compressed pulse. These sidelobes are caused by a combination of the following effects:

1. Output power variations in the BWO contain significant L-band components due to the rapid scan rate. The mixer converts these variations into energy within the compression filter passband, where it appears as baseline clutter.

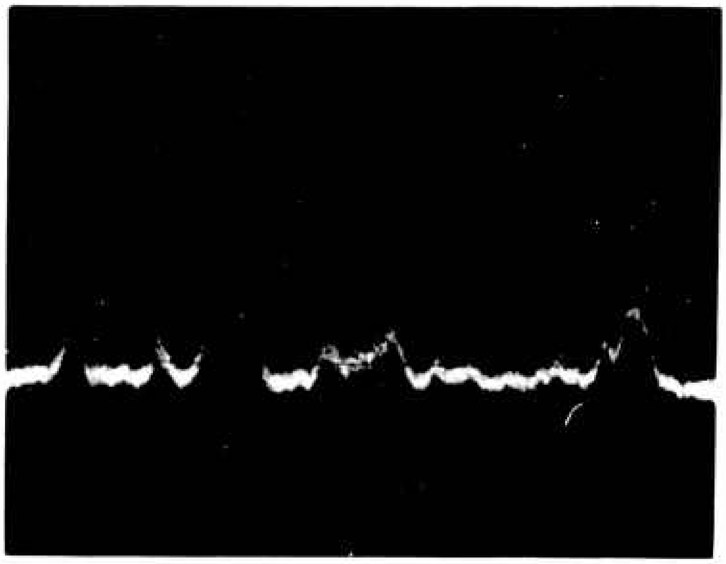


FIG. 22. COMPRESSED PULSE AND SIDELOBES, 10 NSEC/DIV. Main pulse amplitude = 10 divisions.

2. The TWT's used in this test have internal reflections which cause delayed and attenuated replicas of an input pulse to appear at the output for up to 100 nsec following the direct transmission.
3. Imperfect phase cancellation of the compression filter results in peaks of energy outside the region of the compressed pulse.
4. The instantaneous frequency of the scanning excitation deviates from linear variation by ±10 Mc at several points in the sweep.

Most of the sidelobes of Fig. 22 are caused by effects 3 and 4. The two largest ones, however, are due to effects 1 and 2. The peak preceding the pulse by 50 nsec is due to direct detection and is 20 db lower than the main pulse. The peak following the main pulse by 20 nsec is also down 20 db and is due to TWT reflections. The sidelobes due to the compression filter appear to be at least 23 db lower in amplitude than the compressed pulse.

C. CONCLUSIONS FROM EXPERIMENTAL RESULTS

The test filter performance provided a substantial improvement over that of other techniques previously used at Stanford to obtain pulse compression at microwave frequencies. The most serious drawback of this type of microwave filter is the relatively high insertion loss. The use of directional couplers as taps would alleviate this objection while simultaneously providing an easily adjustable weighting. It appears that a filter with a considerably larger time-bandwidth product could be constructed using this technique with a longer delay line and more taps, the limiting factor probably being the accuracy with which the excitation function could be generated.

IV. CONCLUSIONS AND RECOMMENDATIONS

The computational results described indicate that the tapped-delay-line compression filter can perform competitively with many other systems. Some systems making use of tapped delay lines have used bandpass filters on the individual taps in order to suppress the grating lobes that are produced as a result of the low number of taps. It is possible that this apparent preference for the tuned-tap compression filter is due to the difficulty of predicting the response of the untuned-tap filter by analytic methods. The advent of the high-speed computer has eliminated this objection to the use of the untuned-tap filter and should allow this filter to be seriously considered for many pulse-compression applications.

The experimental filter has shown that even a very simple construction technique can provide a compression filter whose performance rivals much more complicated systems [Ref. 4]. No attempt was made with the experimental filter to realize the potential performance of the tapped delay line due to the limitations imposed upon the compression system by other components.

The recent development of much improved BWO's makes it possible to generate broadband (4 Gc) frequency sweeps with a maximum frequency deviation from linearity of only ±0.1 percent of the total bandwidth swept. Measurements on one tube* indicate that this linearity can be maintained at scan rates greater than 20 Mc/nsec. The fine-grain power variations of this tube are also much improved over that of the system used for testing the experimental filter. Reduction of these power variations would have the effect of reducing the spurious responses present in the compression-filter output due to direct detection of the local-oscillator rf envelope.

These improvements make it possible to realize more of the potential of the compression filter in an actual system. Thus it appears that the construction of a filter with the weightings derived by the computer program would justify the effort if the new filter were used in a system

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*A Varian VA-175G backward wave oscillator manufactured by Varian Associates, Palo Alto, California.

employing presently available BWO's. Such an improved system might still be limited by internal reflections in the TWT amplifiers, although not to the extent that the test filter described here was limited. Because of the high losses in the experimental filter, the TWT amplifier had to be driven to saturation in order to obtain a sufficient signal-to-noise ratio at the sampling oscilloscope for observing the sidelobes. The spurious signals generated by reflection within the TWT appear about 20 db lower in amplitude than the primary signal when the tube is near saturation, but drop an additional 10 db lower if the power level is kept at least 10 db below saturation. Several manufacturers have recently placed tubes on the market which are capable of delivering 10 w over an octave band while maintaining noise figures of 15 db or better. One of these tubes should nearly eliminate the TWT as a source of sidelobes.

The tapped delay line, although treated in this report as a microwave device, is certainly not restricted to microwave frequencies. A 100-tap-delay-line compression filter centered at 500 kc has been used in a scanning spectrum analyzer system at Stanford [Ref. 5]. Corning Glass Works [Ref. 6] describes a glass ultrasonic delay line with as many as 1000 taps and a potential bandwidth of about 20 Mc. The large numbers of taps involved with these filters make the contribution of any individual tap a very small percentage of the total response. The computer then becomes the only practical method of finding the tap weighting which provides the best response for a given application.

APPENDIX A. COMPUTER-PROGRAM FLOW CHART

1. Definitions of Terms Used in Flow Chart

A	if $-10 > \mathrm{TMTAU} > 60$, A = 0.0 else A = 1, or $A = 1 - [0.0081632653\ (\mathrm{TMTAU} - 25)^2]$
A1	minimum value of amplitude range
A2	maximum value of amplitude range
AMPC	amount of amplitude equal to 1 in. on amplitude axis
AMPLNG	length of amplitude axis in inches ($\geq$10.0)
AMPRNG	reciprocal of amplitude range (scale factor for total plot)
AP	parameter of PKCALC used to obtain valid set of τ's or B's depending upon which is being perturbed
ARNGID	scale factor of amplitude for plot which skips the main lobe
AT	parameter of PKCALC used to obtain valid set of τ's or B's depending upon which is being perturbed at a given time
ATICK()	values of 10, 5, 2.5, 1.25 or 1 (in percent) of PKMAX1 used for tick marks on left side of plot
A(TMTAU)	calculate multiplier of cos function ESUM
AXPLOT(ARNG)	plots time axis and box
B1	current value of BP()
B2	current value of BT() if perturbing B, else holds B1
BP()	matrix of valid set of B values
BT()	matrix of tested B values
BTICK()	same as ATICK() except for right side of plot

CHANGE	decimal representation of percent change peak-to-sidelobe ratio for cutoff
CHNG	change in peak-to-sidelobe ratio magnitude
EO(,)	value of r(t) with second index used to indicate permanent or temporary set--thereby used as a switch to indicate valid function
EREV	calculate r(t) for perturbed τ or B
ESUM	r(t)
ESUM(TIME)	calculate r(t) at T = TIME for given TAUP() and BP() (initial summation)
ET1	r(t) of first point of main lobe, valid
ET2	r(t) of last point of main lobe, valid
ET3	scaled value of ET1
ET4	scaled value of ET2
IB	flag for calculating or reading in B's
ICNT	counts the number of perturbations of τ's and B's
IFLAG	flag to indicate which set is being perturbed (0 for τ, 1 for B)
IM1	I minus 1
IPERM	index to indicate valid set of given matrix quantity
ITAU	flag for calculating or reading in τ's
ITEMP	index to indicate tested set of given matrix quantity
IT12	number of time points within area of interest
ITM1	matrix value of first point to begin expecting main lobe
ITM1M1	last matrix point before main lobe section
ITM2	matrix value of last point to expect main lobe

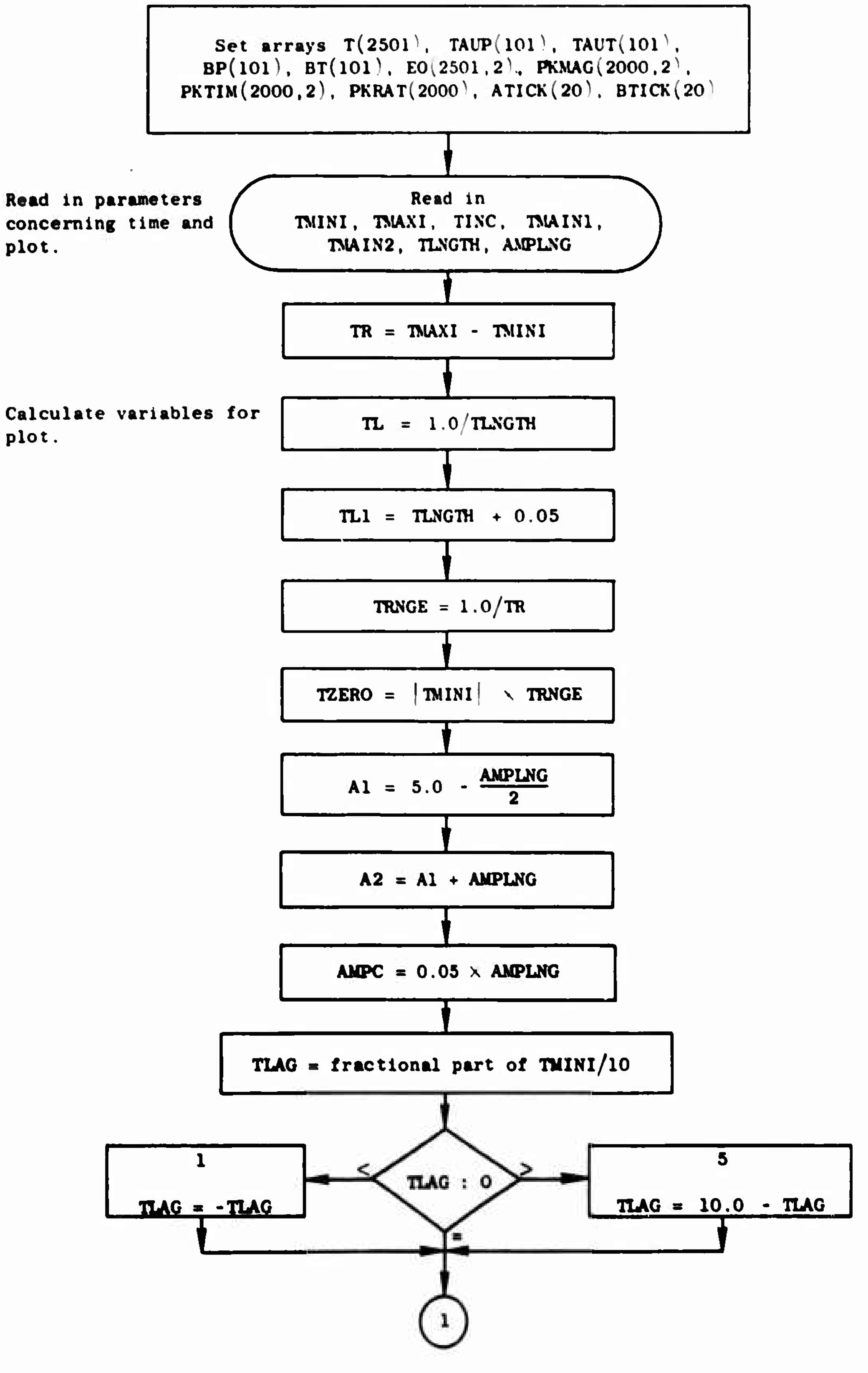
ITM2P1	first matrix point after main lobe section
LASTT	number of tick marks on time axis
MAXCNT	number of runs through τ's and B's allowed
N1	first tap number
N1NC	increment of n
N1P1	second tap
N2	last tap number $\geq$ 101
NOPKS=NPK	the quantity on the left is the temporary equivalent of the one on the right within PKCALC when a new set of τ's or B's is being tried. Changing a set in value replaces the set on the right by that on the left
NPK	number of peaks
NPK1	number of peaks in area before main lobe is encountered
NPK2	number of peaks from start through end of main lobe area
N2M1	next to last tap
PKCALC(AP,AT)	calculate new possible set of peaks
PKMAG(,)	matrix to hold peak values--last index to switch valid groups
PKMAX1	magnitude of maximum peak--eventually main lobe
PKMAX2	magnitude of second largest peak--eventually maximum sidelobe
PKRAT()	matrix to hold ratio of main lobe to peaks
PKTIM1	time of PKMAX1
PKTIM2	time of PKMAX2
PLOT1	plots initial and final plots

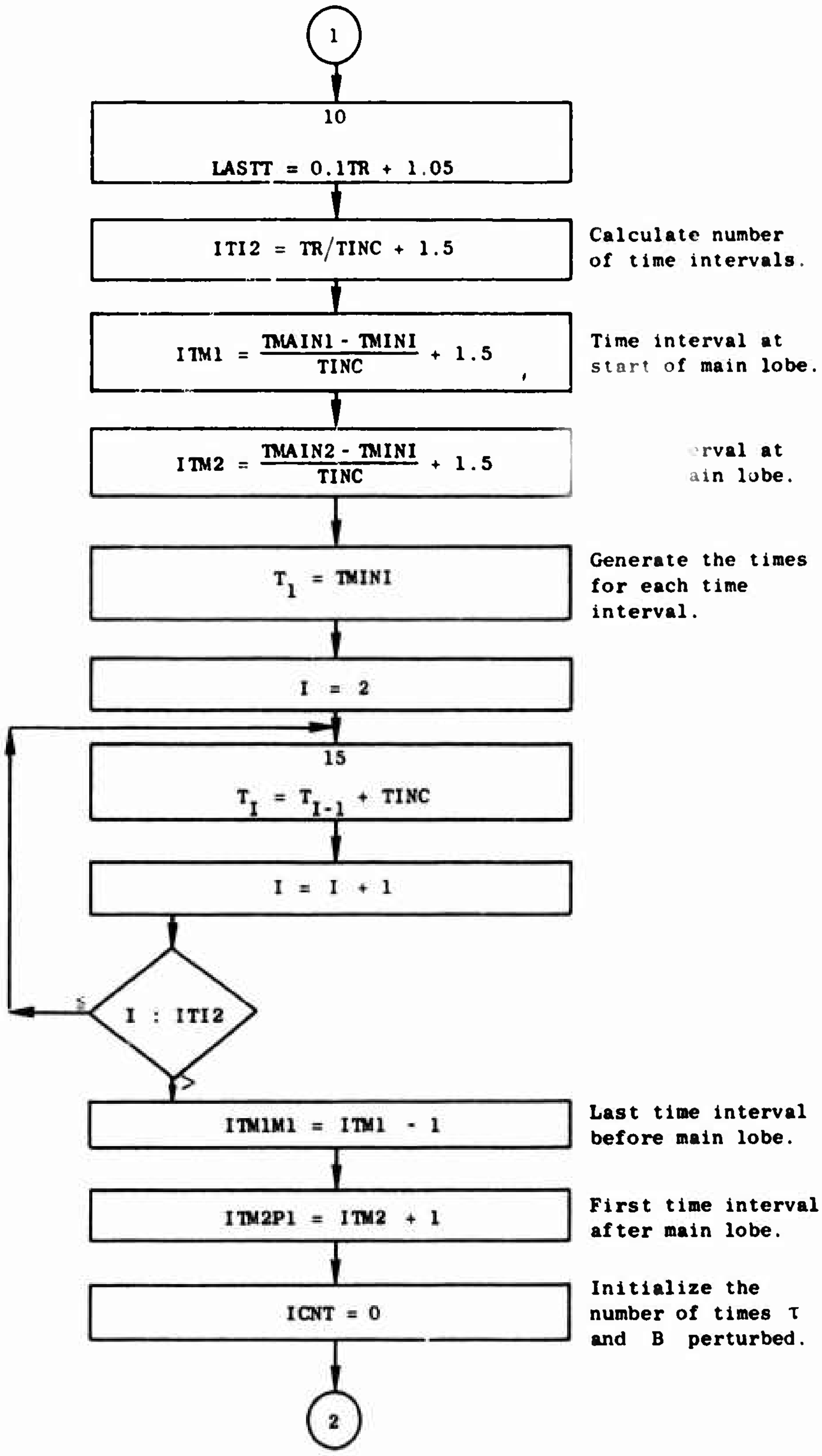
PLOT2	plots intermediate data
PRES	indicator by sign of slope between last two points
PREV	indicator by sign of slope between the previous last two points
PROD	indicator of whether a perturbation will increase or decrease the value of τ
RATIO	ratio at beginning of a set of perturbations
RATIO1	current ratio for best case (peak main lobe/maximum sidelobe)
SAVE	holds the last magnitude of the last peak
SPKMAX	actual value of PKMAX1
STPMAX=SPKMAX	same as NOPKS=NPK
T()	matrix of time value
TAU	$100\sqrt{1.01 - 0.01(N)} - 50.0$
TAU1	current value of TAUP()
TAU2	current value of TAUT() if perturbing τ, else holds TAU1
TAU(FLN)	calculate TAUP() if not read in
TAUINC	perturbation increment of τ
TAUMAX	maximum allowable value of any τ
TAUP()	matrix of valid set of τ values
TAUT()	matrix of tested set of τ values
TICKS	calculates the values of the tick marks on the amplitude axis
TIME	T(), for calculation of r(t)
TINC	time increment for all time variables (sec)
TL	reciprocal of length of time axis (used in plotting)

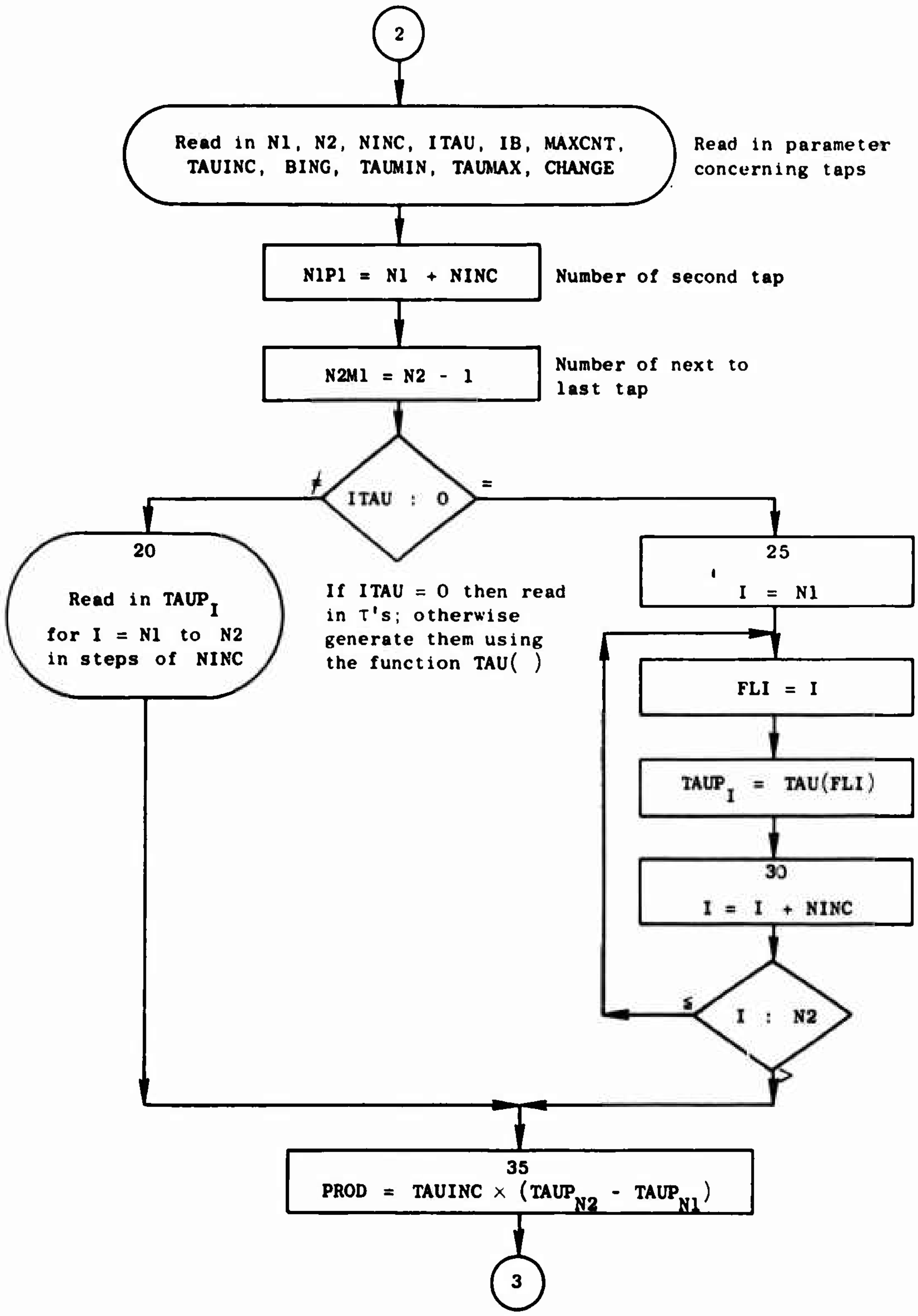
TL1	length of time axis plus 0.05 in. (used in plot ticks)
TLAG	plotting constant for time tick marks
TLNGTH	length of plot-time axis (inches)
TMAIN1	minimum time to begin expecting main lobe
TMAIN2	time to stop expecting main lobe
TMINI,TMAXI	beginning and end of the time interval within which the peak-to-sidelobe ratio is optimized
TMTAU	$T - \tau$
TMTAU1	time minus TAU1
TMTAU2	time minus TAU2
TPMAX1=PKMAX1	same as NOPKS=NPK
TPMAX2=PKMAX2	same as NOPKS=NPK
TPTIM1=PKTIM1	same as NOPKS=NPK
TPTIM2=PKTIM2	same as NOPKS=NPK
TR	total range of time
TRATIO=RATIO1	same as NOPKS=NPK
TRNGE	amount of time equivalent to 1 in. on time axis
TZERO	number of time-axis inches equal to the minimum time used to shift time axis to zero

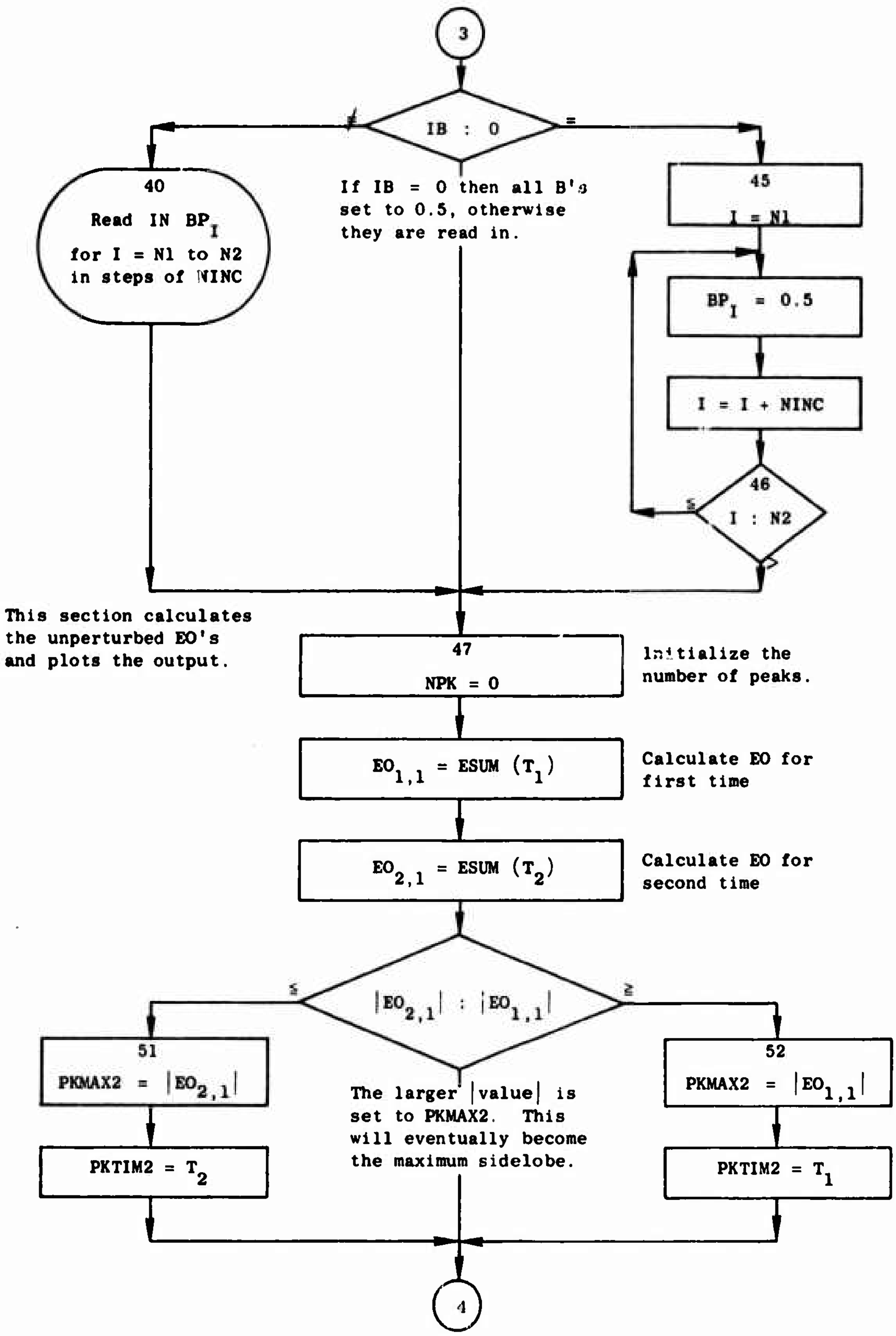
2. Flow Chart Diagram

A detailed flow chart, which describes in nonsyntactical language the program listed in Appendix B, is given on pages 40 through 58. Descriptive notations, as well as statement numbers, are included within the flow chart where appropriate.

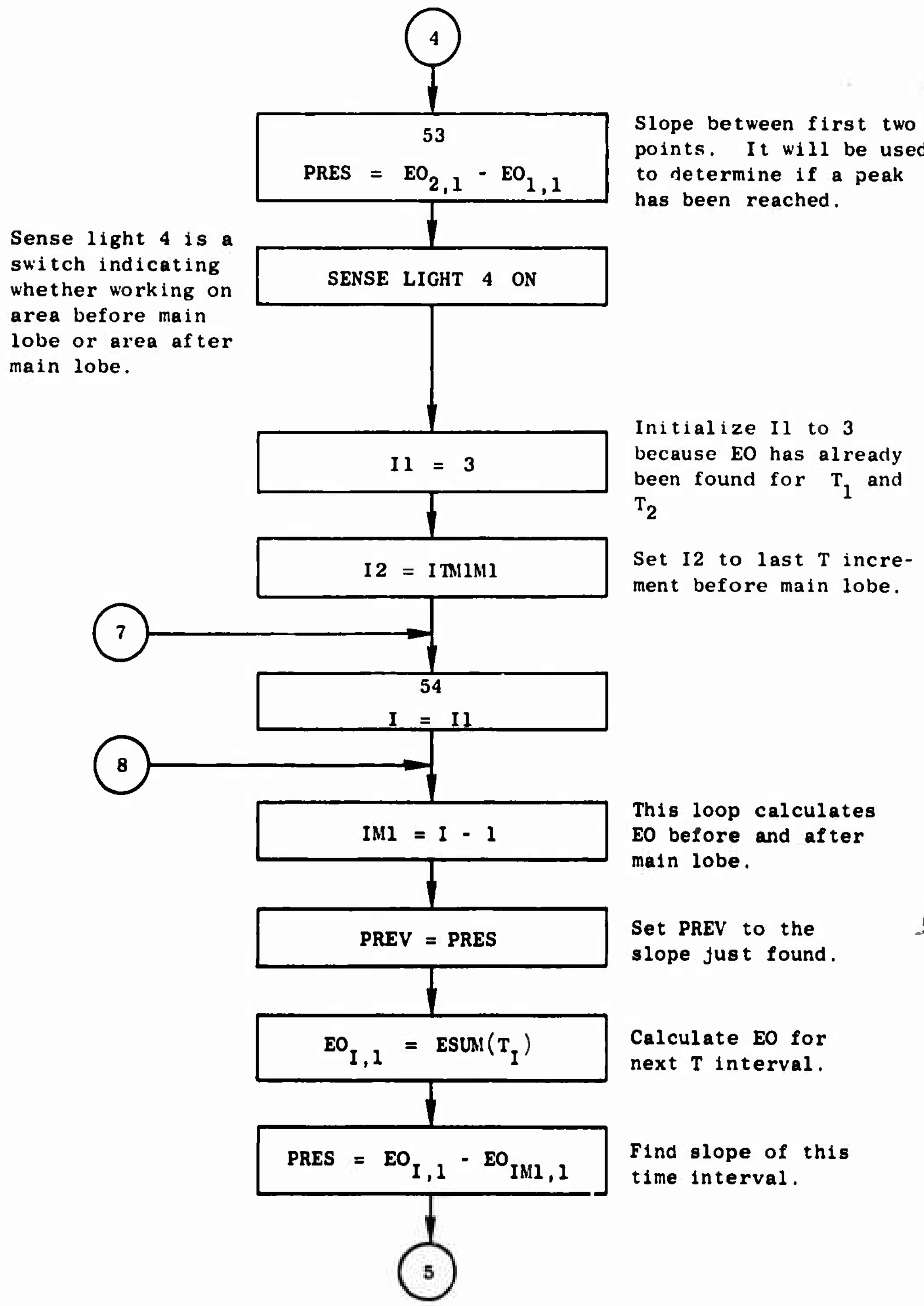

Set arrays T(2501), TAUP(101), TAUT(101), BP(101), BT(101), EO(2501,2), PKMAG(2000,2), PKTIM(2000,2), PKRAT(2000), ATICK(20), BTICK(20)
Read in parameters concerning time and plot.
Read in TMINI, TMAXI, TINC, TMAIN1, TMAIN2, TLNGTH, AMPLNG
TR = TMAXI - TMINI
Calculate variables for plot.
TL = 1.0/TLNGTH
TL1 = TLNGTH + 0.05
TRNGE = 1.0/TR
TZERO = |TMINI| × TRNGE
A1 = 5.0 - AMPLNG/2
A2 = A1 + AMPLNG
AMPC = 0.05 × AMPLNG
TLAG = fractional part of TMINI/10
TLAG : 0
<
>
=
1
TLAG = -TLAG
5
TLAG = 10.0 - TLAG
1

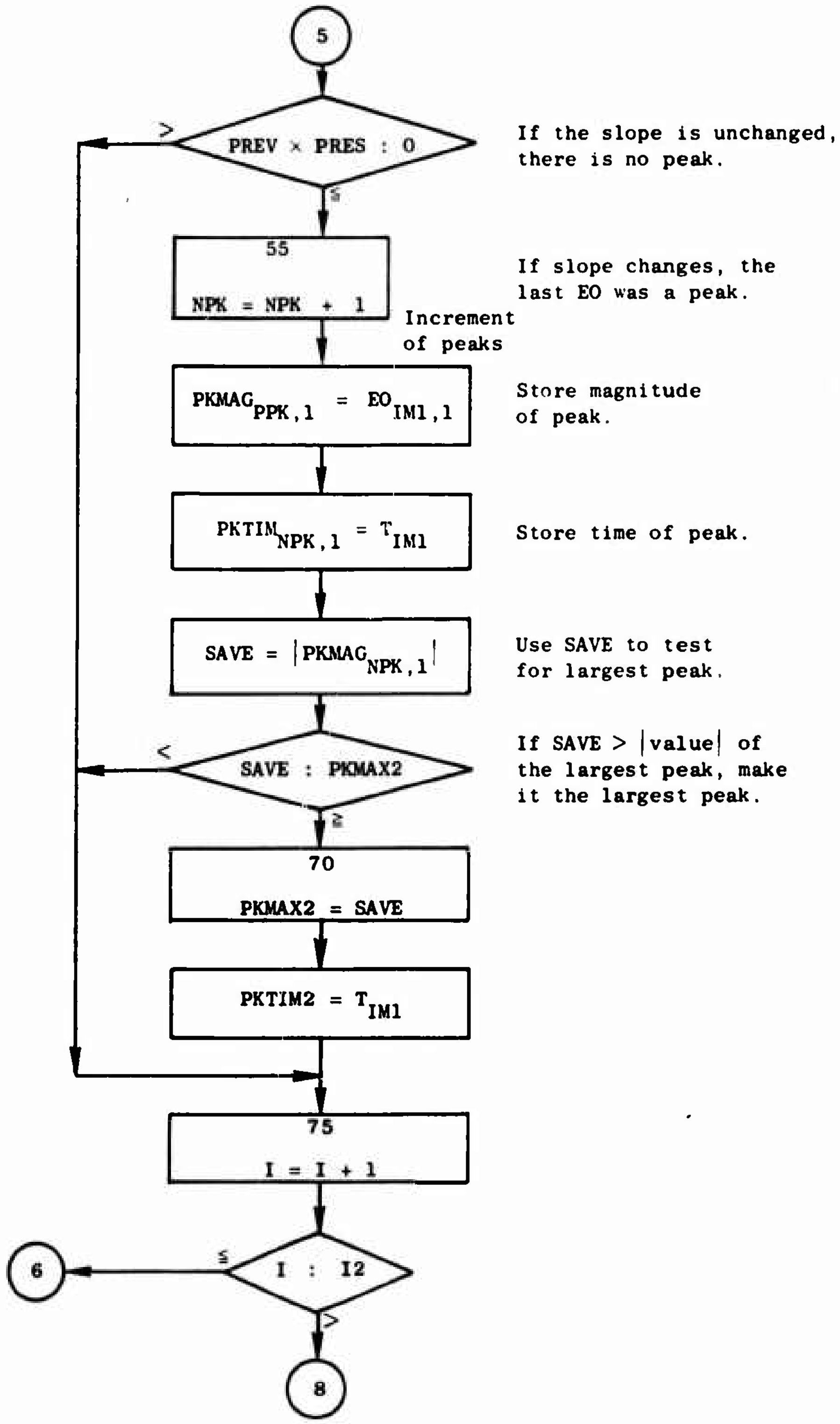

1
10
LASTT = 0.1TR + 1.05
ITI2 = TR/TINC + 1.5
Calculate number of time intervals.
ITM1 = (TMAIN1 - TMINI)/TINC + 1.5
Time interval at start of main lobe.
ITM2 = (TMAIN2 - TMINI)/TINC + 1.5
rval at ain lobe.
T1 = TMINI
Generate the times for each time interval.
I = 2
15
TI = TI-1 + TINC
I = I + 1
I : ITI2
>
ITM1M1 = ITM1 - 1
Last time interval before main lobe.
ITM2P1 = ITM2 + 1
First time interval after main lobe.
ICNT = 0
Initialize the number of times τ and B perturbed.
2

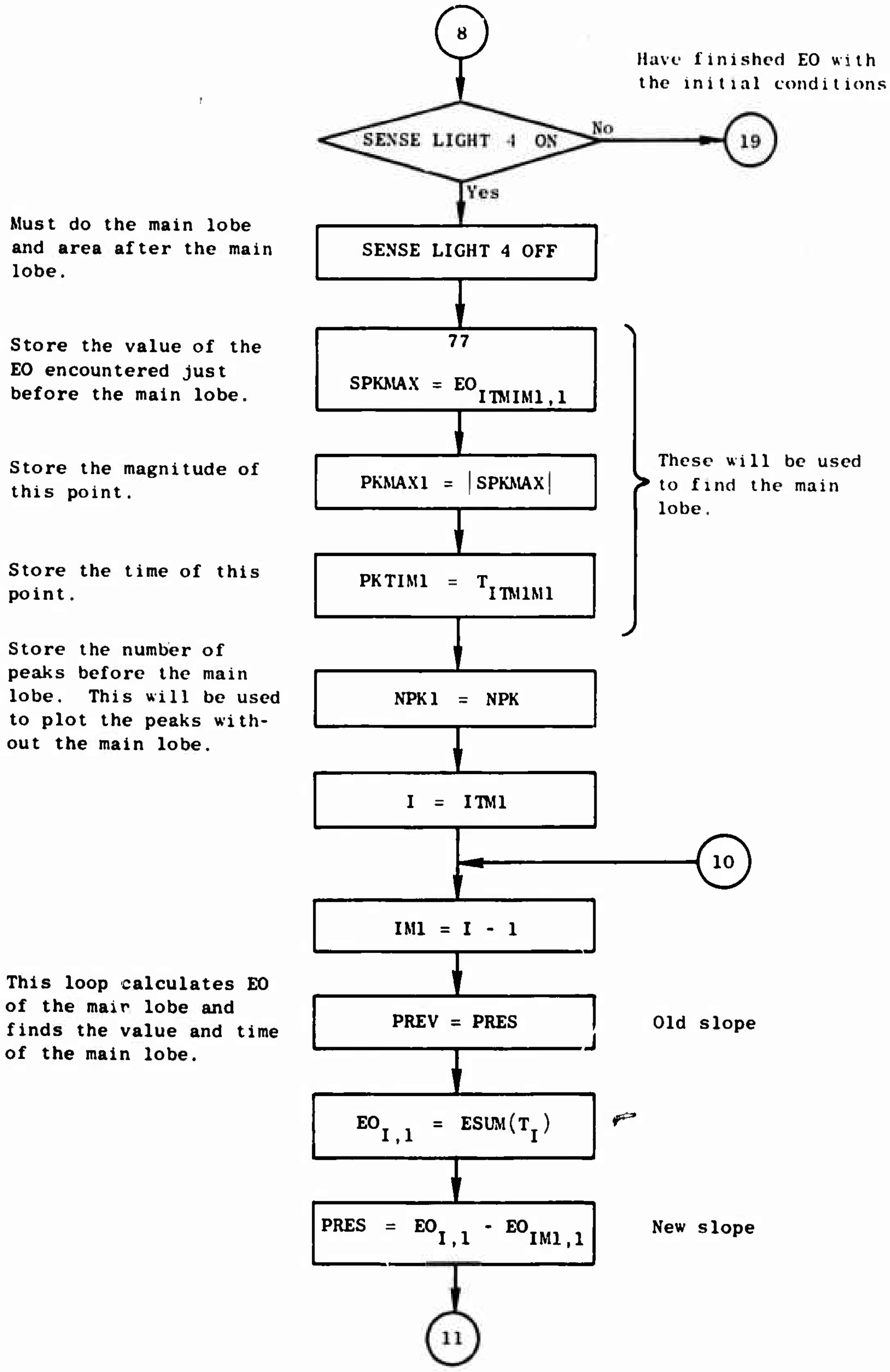

2
Read in N1, N2, NINC, ITAU, IB, MAXCNT, TAUINC, BING, TAUMIN, TAUMAX, CHANGE
Read in parameter concerning taps
N1P1 = N1 + NINC
Number of second tap
N2M1 = N2 - 1
Number of next to last tap
ITAU : 0
≠
=
20
Read in TAUP
I
for I = N1 to N2 in steps of NINC
If ITAU = 0 then read in τ's; otherwise generate them using the function TAU( )
25
I = N1
FLI = I
TAUP
I
= TAU(FLI)
30
I = I + NINC
I : N2
≤
>
35
PROD = TAUINC × (TAUP
N2
- TAUP
N1
)
3

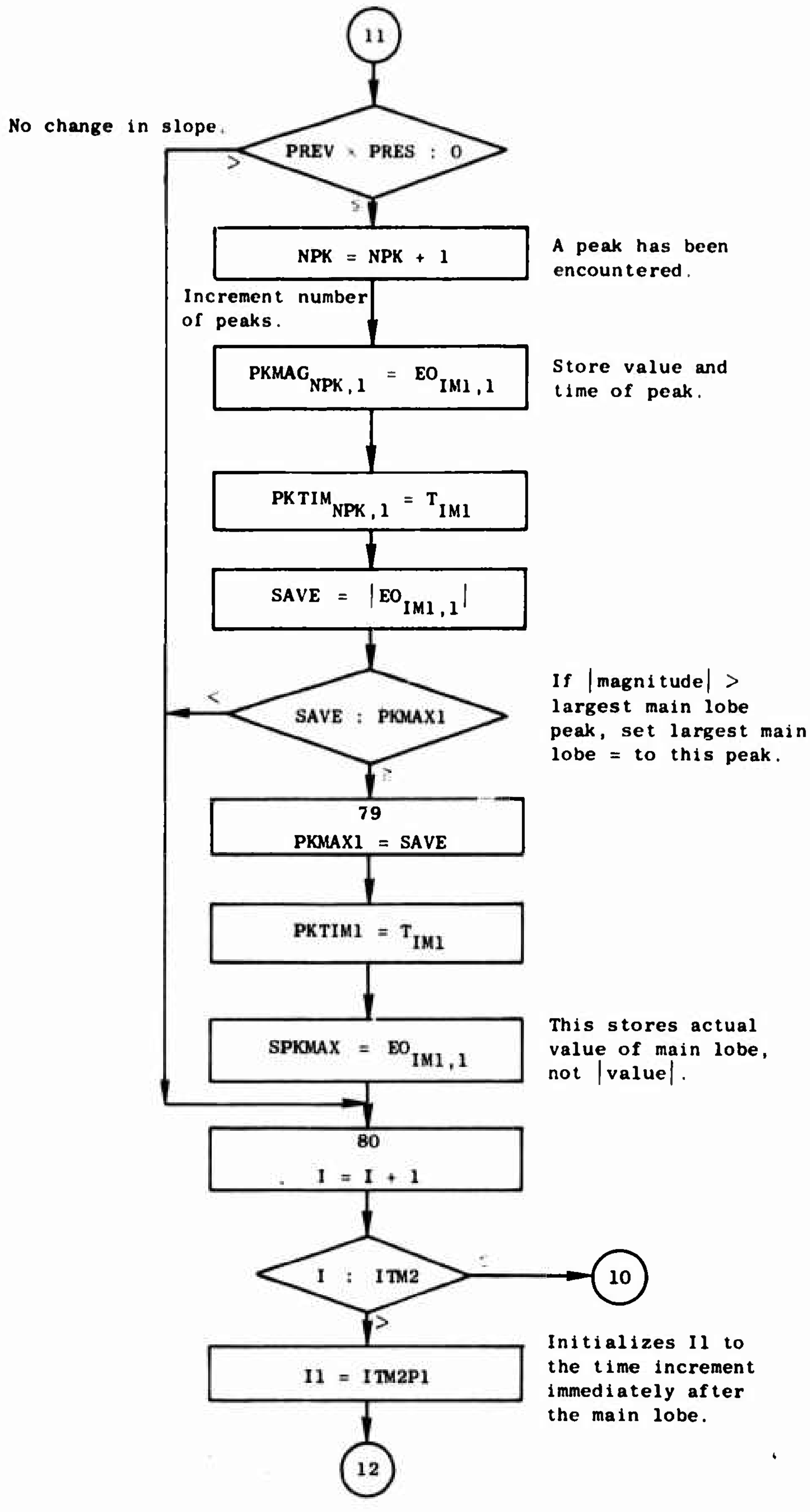


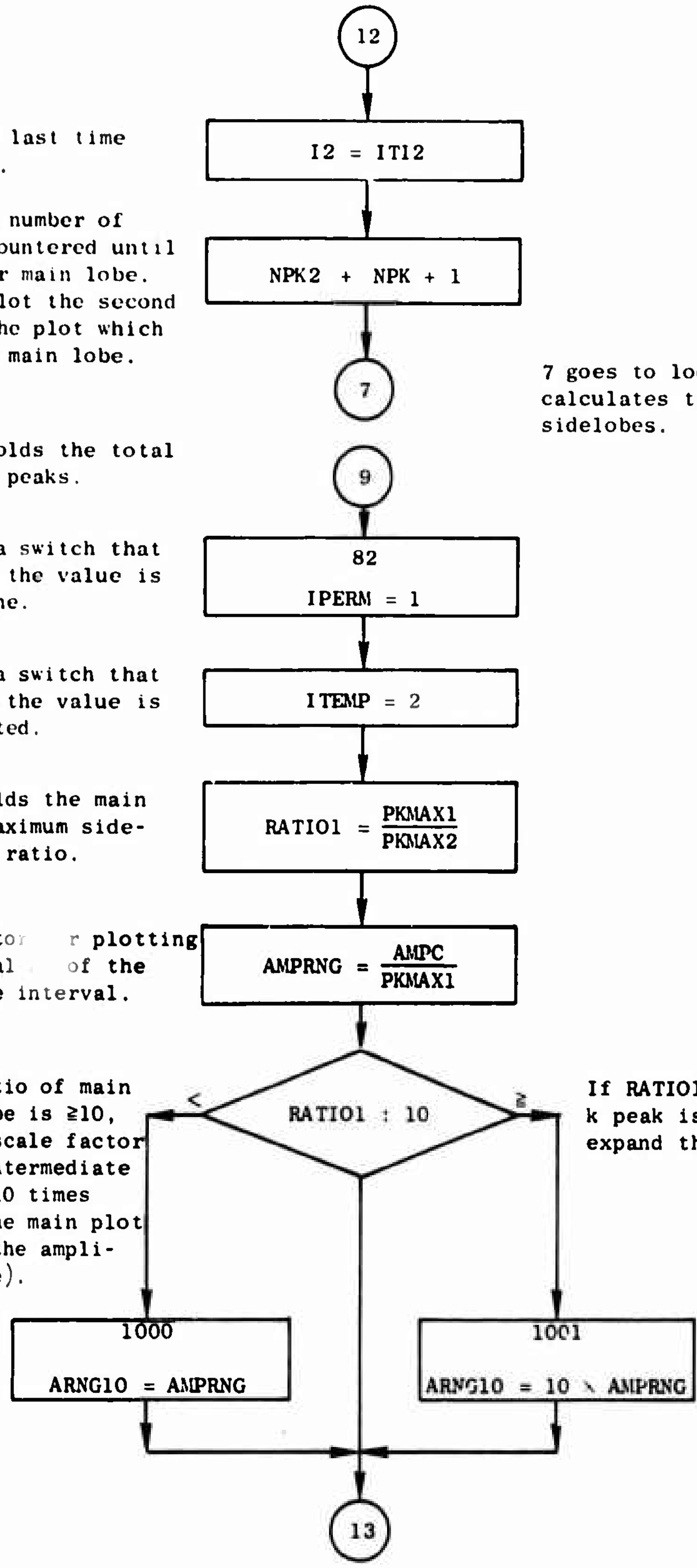
3
IB : 0
≠
=
40
Read IN BP_I
for I = N1 to N2
in steps of NINC
If IB = 0 then all B's
set to 0.5, otherwise
they are read in.
45
I = N1
BP_I = 0.5
I = I + NINC
46
I : N2
≤
>
This section calculates
the unperturbed EO's
and plots the output.
47
NPK = 0
Initialize the
number of peaks.
$EO_{1,1}$ = ESUM (T_1)
Calculate EO for
first time
$EO_{2,1}$ = ESUM (T_2)
Calculate EO for
second time
$|EO_{2,1}|$: $|EO_{1,1}|$
≤
≥
51
PKMAX2 = $|EO_{2,1}|$
PKTIM2 = T_2
The larger |value| is
set to PKMAX2. This
will eventually become
the maximum sidelobe.
52
PKMAX2 = $|EO_{1,1}|$
PKTIM2 = T_1
4


4
53
PRES = EO2,1 - EO1,1
Slope between first two points. It will be used to determine if a peak has been reached.
Sense light 4 is a switch indicating whether working on area before main lobe or area after main lobe.
SENSE LIGHT 4 ON
I1 = 3
Initialize I1 to 3 because EO has already been found for T1 and T2
I2 = ITM1M1
Set I2 to last T increment before main lobe.
7
54
I = I1
8
IM1 = I - 1
This loop calculates EO before and after main lobe.
PREV = PRES
Set PREV to the slope just found.
EOI,1 = ESUM(TI)
Calculate EO for next T interval.
PRES = EOI,1 - EOIM1,1
Find slope of this time interval.
5


5
PREV × PRES : 0
>
≤
If the slope is unchanged, there is no peak.
55
NPK = NPK + 1
Increment of peaks
If slope changes, the last EO was a peak.
PKMAG PPK,1 = EO IM1,1
Store magnitude of peak.
PKTIM NPK,1 = T IM1
Store time of peak.
SAVE = |PKMAG NPK,1|
Use SAVE to test for largest peak.
SAVE : PKMAX2
<
≥
If SAVE > |value| of the largest peak, make it the largest peak.
70
PKMAX2 = SAVE
PKTIM2 = T IM1
75
I = I + 1
I : I2
≤
>
6
8


8
Have finished EO with the initial conditions.
SENSE LIGHT 4 ON
No
19
Yes
Must do the main lobe and area after the main lobe.
SENSE LIGHT 4 OFF
Store the value of the EO encountered just before the main lobe.
77
SPKMAX = EO ITMIM1,1
Store the magnitude of this point.
PKMAX1 = |SPKMAX|
These will be used to find the main lobe.
Store the time of this point.
PKTIM1 = T ITM1M1
Store the number of peaks before the main lobe. This will be used to plot the peaks without the main lobe.
NPK1 = NPK
I = ITM1
10
IM1 = I - 1
This loop calculates EO of the main lobe and finds the value and time of the main lobe.
PREV = PRES
Old slope
EO I,1 = ESUM(T I)
PRES = EO I,1 - EO IM1,1
New slope
11


11
No change in slope.
PREV × PRES : 0
>
NPK = NPK + 1
A peak has been encountered.
Increment number of peaks.
PKMAG$_{NPK,1}$ = EO$_{IM1,1}$
Store value and time of peak.
PKTIM$_{NPK,1}$ = T$_{IM1}$
SAVE = |EO$_{IM1,1}$|
SAVE : PKMAX1
<
If |magnitude| > largest main lobe peak, set largest main lobe = to this peak.
79
PKMAX1 = SAVE
PKTIM1 = T$_{IM1}$
SPKMAX = EO$_{IM1,1}$
This stores actual value of main lobe, not |value|.
80
I = I + 1
I : ITM2
10
>
I1 = ITM2P1
Initializes I1 to the time increment immediately after the main lobe.
12



I2 set to last time increment.

Holds the number of peaks encountered until area after main lobe. Used to plot the second half of the plot which skips the main lobe.

7 goes to loop which calculates the initial sidelobes.

NPK now holds the total number of peaks.

IPERM is a switch that indicates the value is a valid one.

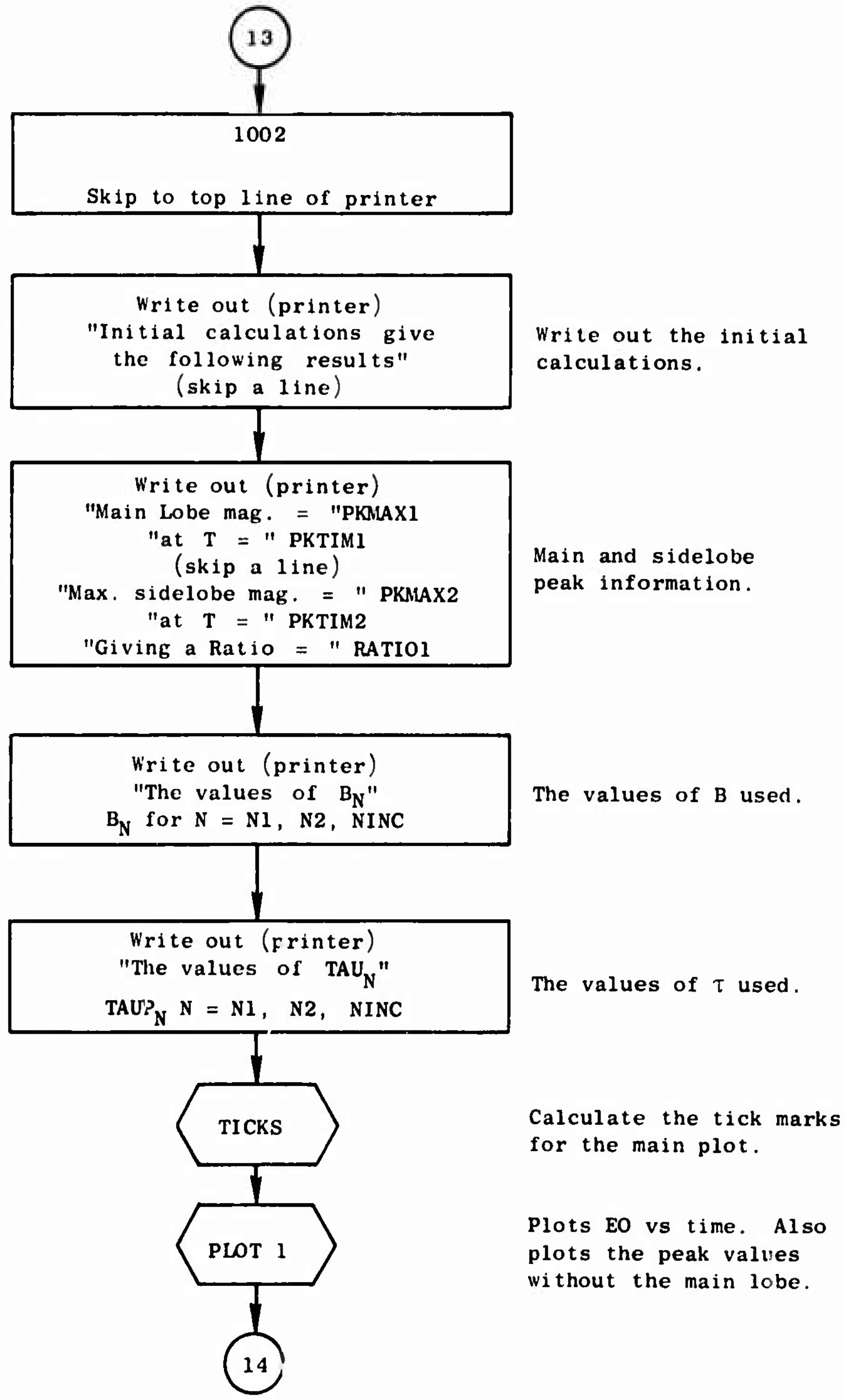
ITEMP is a switch that indicates the value is being tested.

RATIO1 holds the main lobe to maximum side-lobe peak ratio.

Scale facto r plotting the initial of the total time interval.

If the ratio of main to sidelobe is ≥10, then the scale factor for the intermediate plots is 10 times that of the main plot (expands the amplitude scale).

If RATIO1 < 10, sidelobe k peak is too large to expand the scale.


13
1002
Skip to top line of printer
Write out (printer)
"Initial calculations give
the following results"
(skip a line)
Write out the initial calculations.
Write out (printer)
"Main Lobe mag. = "PKMAX1
"at T = " PKTIM1
(skip a line)
"Max. sidelobe mag. = " PKMAX2
"at T = " PKTIM2
"Giving a Ratio = " RATIO1
Main and sidelobe peak information.
Write out (printer)
"The values of B_N"
B_N for N = N1, N2, NINC
The values of B used.
Write out (printer)
"The values of TAU_N"
$TAU?_N$ N = N1, N2, NINC
The values of τ used.
TICKS
Calculate the tick marks for the main plot.
PLOT 1
Plots EO vs time. Also plots the peak values without the main lobe.
14

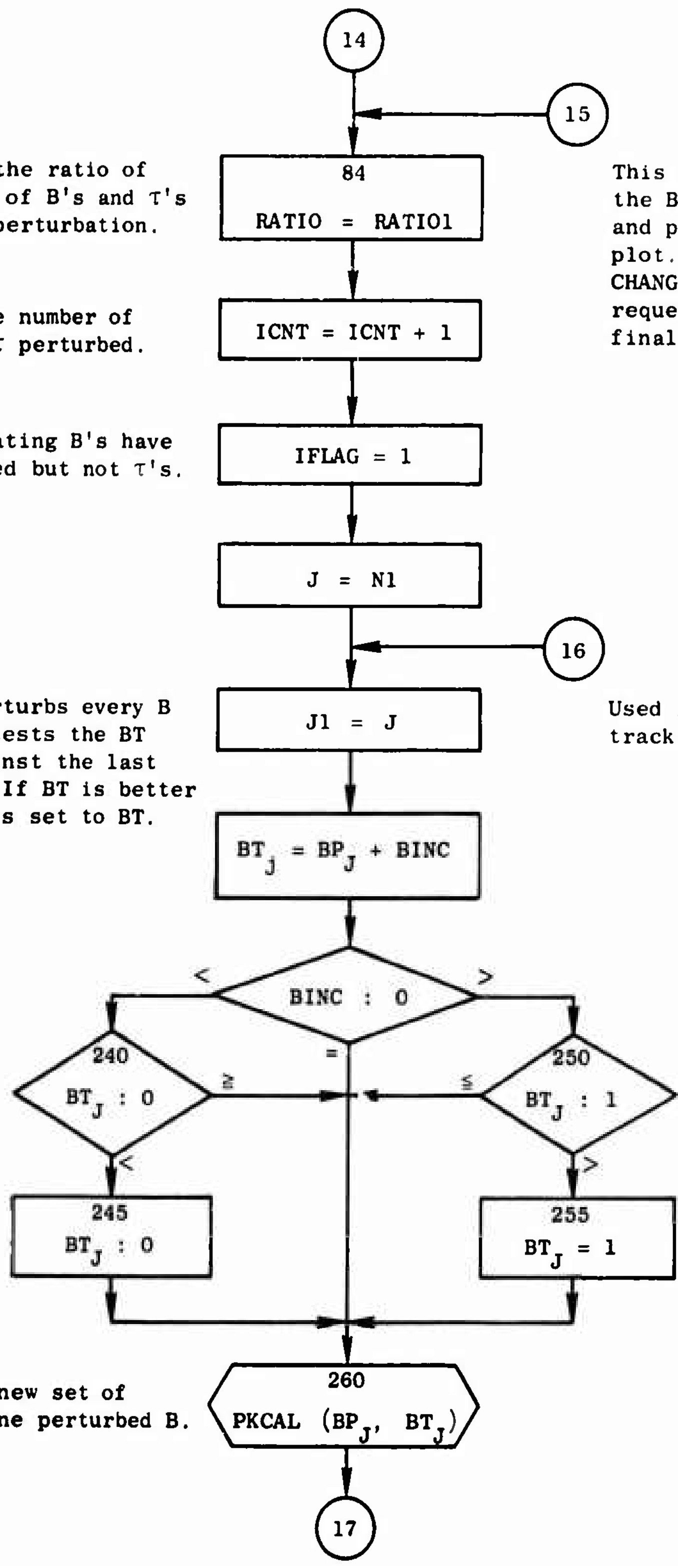
RATIO holds the ratio of the last set of B's and τ's before this perturbation.

Increment the number of times B and τ perturbed.

Switch indicating B's have been perturbed but not τ's.

This loop perturbs every B by BINC and tests the BT (tested) against the last BP (valid). If BT is better than BP, it is set to BT.

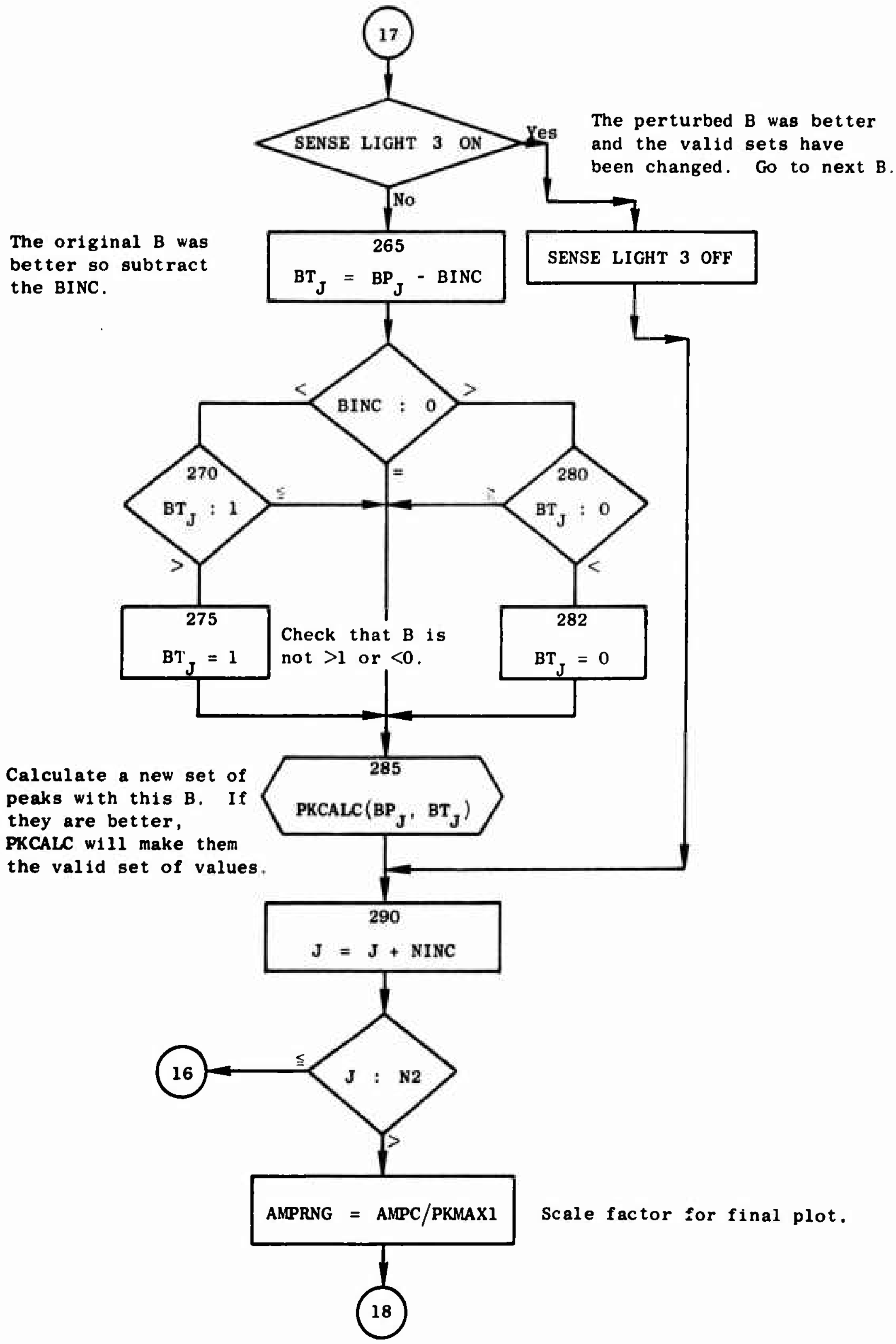
Calculates a new set of peaks using one perturbed B.



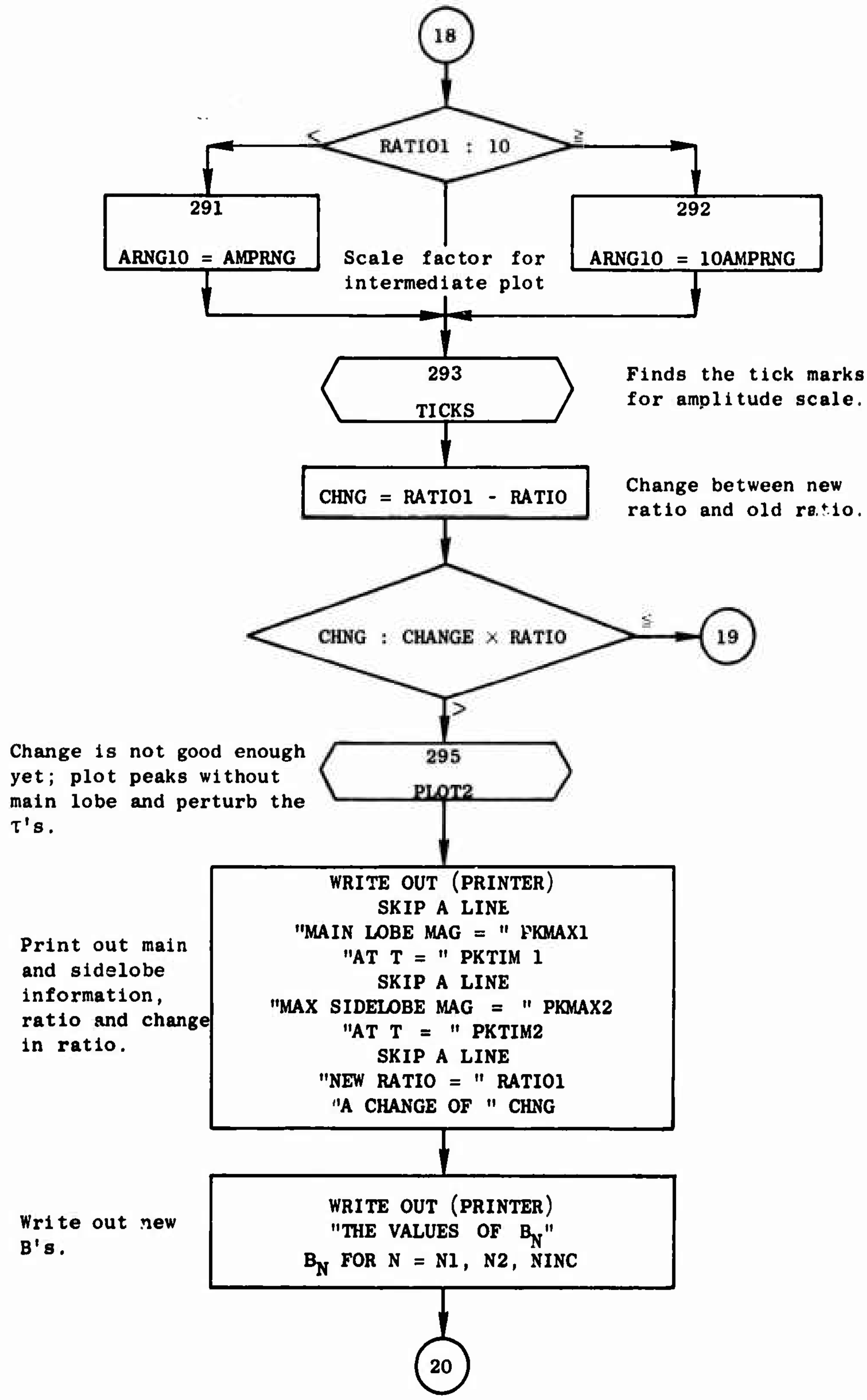
This section perturbs the B's, tests them, and plots an intermediate plot. If within the CHANGE (see step 20) requested, plots the final plot and stops.

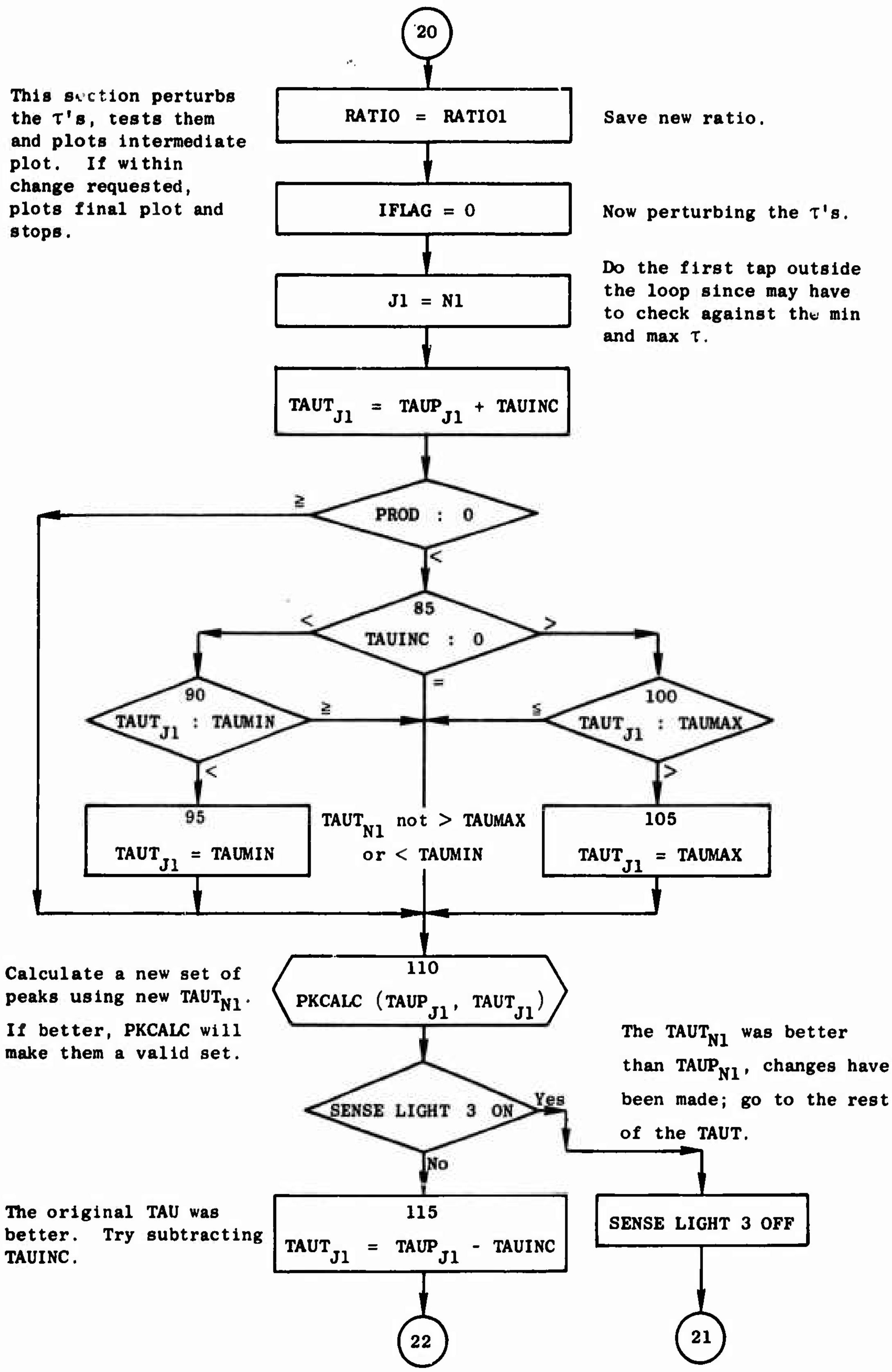
Used in EREV to keep track of tap 3.

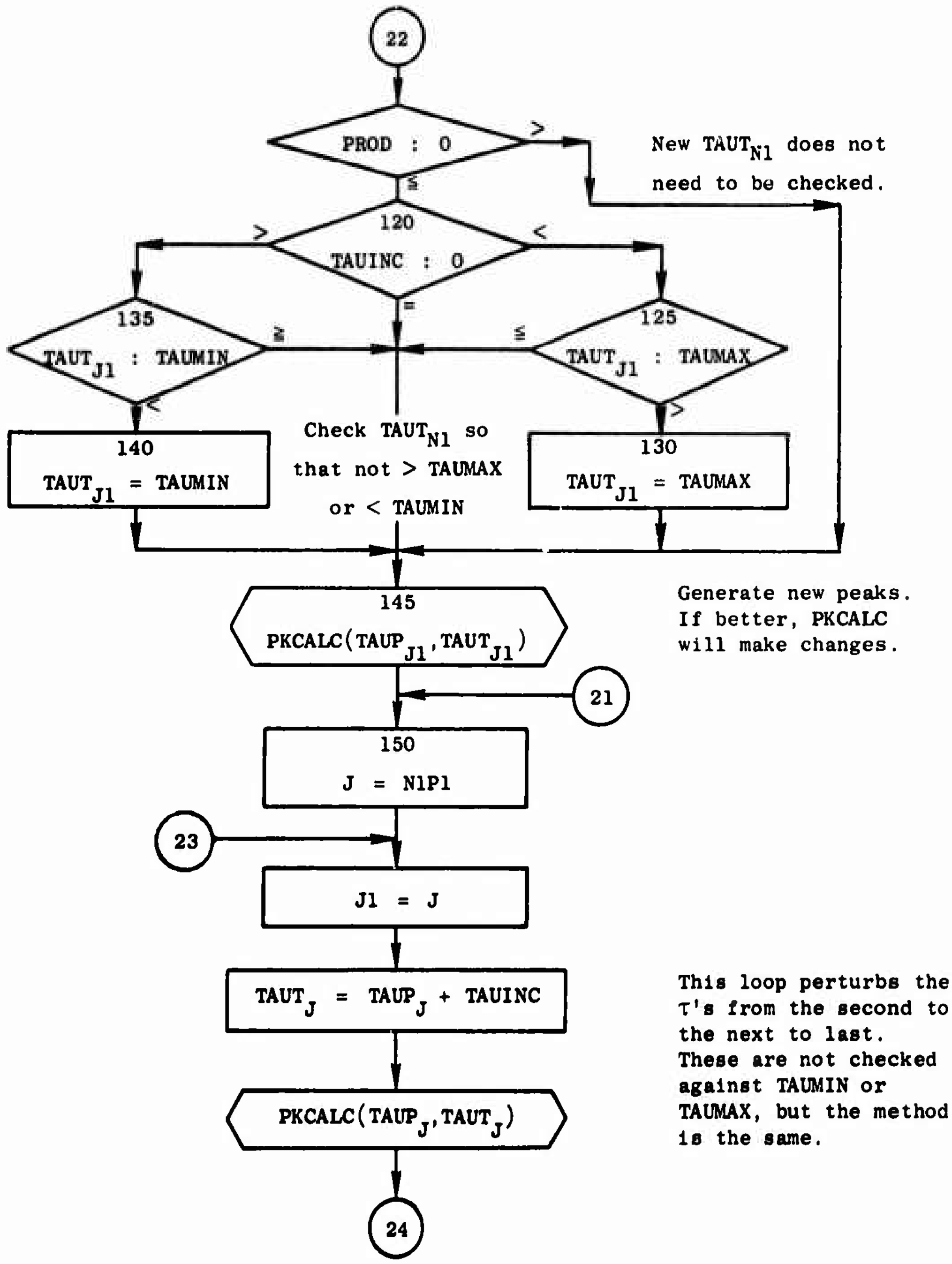
Check to see that BT is not >1 or <0.

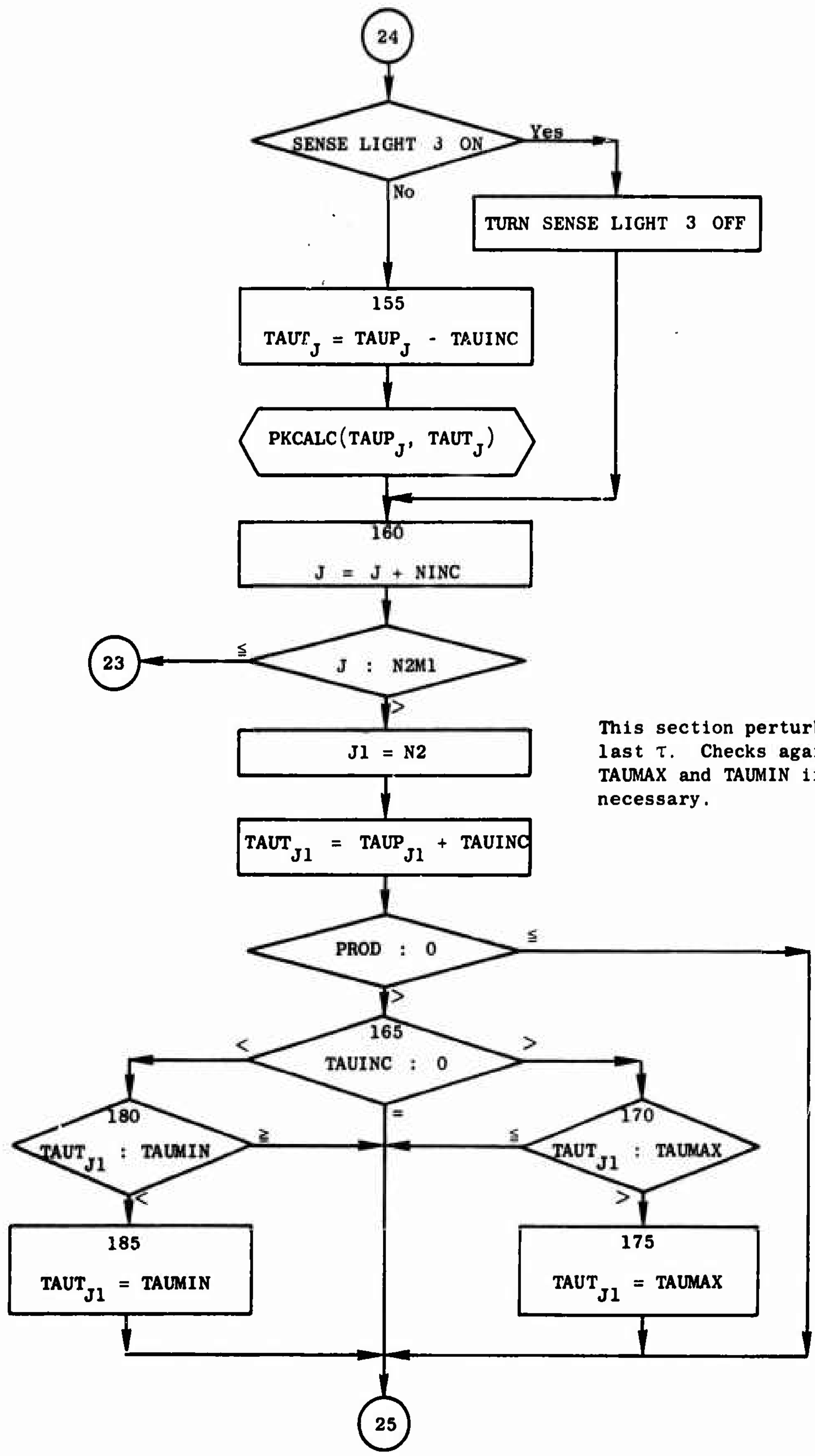


17
SENSE LIGHT 3 ON
Yes
No
The perturbed B was better and the valid sets have been changed. Go to next B.
The original B was better so subtract the BINC.
265
$BT_J = BP_J - BINC$
SENSE LIGHT 3 OFF
BINC : 0
<
>
=
270
$BT_J : 1$
≤
>
280
$BT_J : 0$
≥
<
275
$BT_J = 1$
Check that B is not >1 or <0.
282
$BT_J = 0$
Calculate a new set of peaks with this B. If they are better, PKCALC will make them the valid set of values.
285
$PKCALC(BP_J, BT_J)$
290
J = J + NINC
J : N2
≤
16
>
AMPRNG = AMPC/PKMAX1
Scale factor for final plot.
18

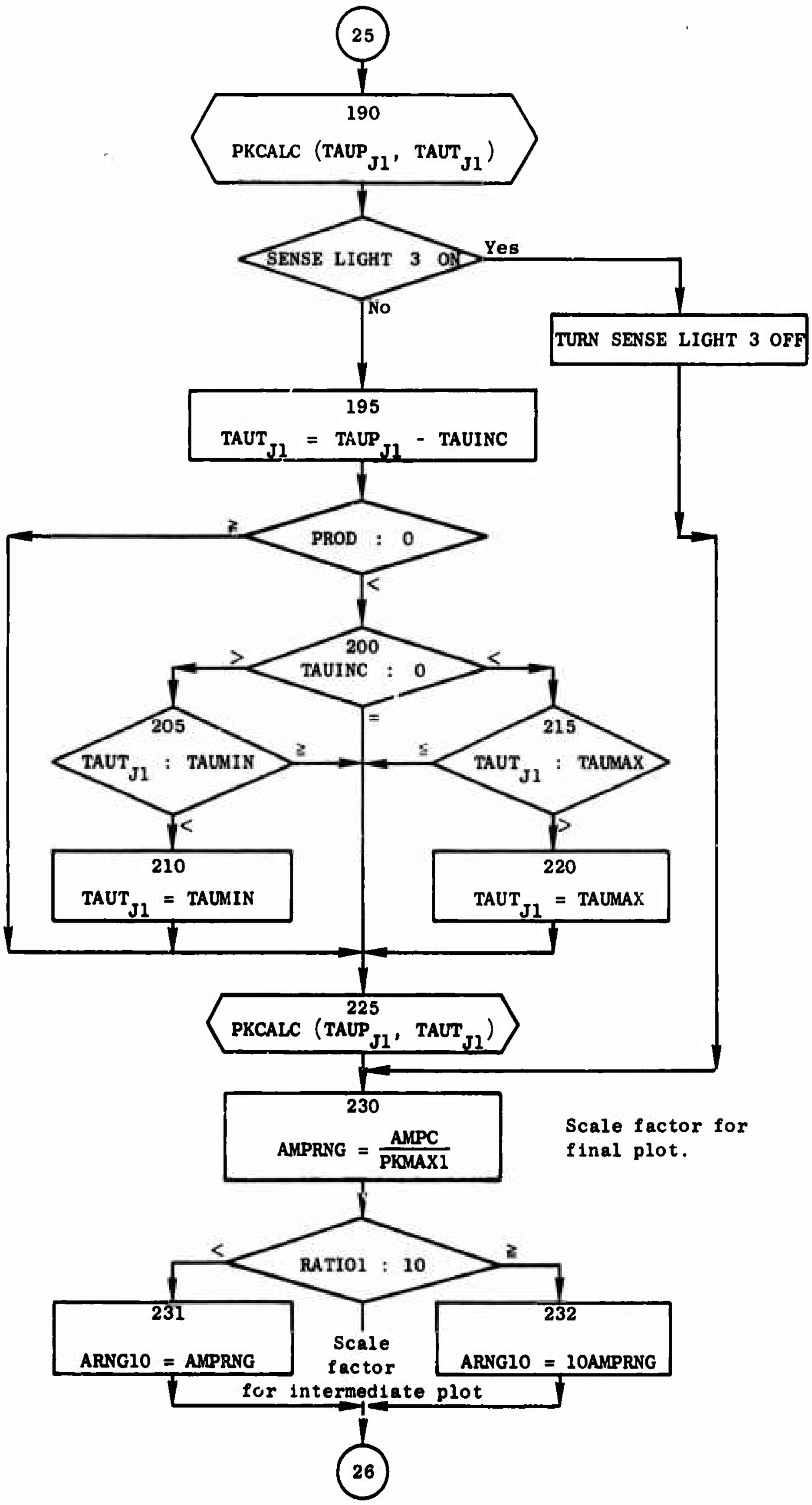

18
RATIO1 : 10
<
≥
291
ARNG10 = AMPRNG
Scale factor for intermediate plot
292
ARNG10 = 10AMPRNG
293
TICKS
Finds the tick marks for amplitude scale.
CHNG = RATIO1 - RATIO
Change between new ratio and old ratio.
CHNG : CHANGE × RATIO
≤
19
>
Change is not good enough yet; plot peaks without main lobe and perturb the τ's.
295
PLOT2
WRITE OUT (PRINTER)
SKIP A LINE
"MAIN LOBE MAG = " PKMAX1
"AT T = " PKTIM 1
SKIP A LINE
"MAX SIDELOBE MAG = " PKMAX2
"AT T = " PKTIM2
SKIP A LINE
"NEW RATIO = " RATIO1
"A CHANGE OF " CHNG
Print out main and sidelobe information, ratio and change in ratio.
WRITE OUT (PRINTER)
"THE VALUES OF B_N"
B_N FOR N = N1, N2, NINC
Write out new B's.
20

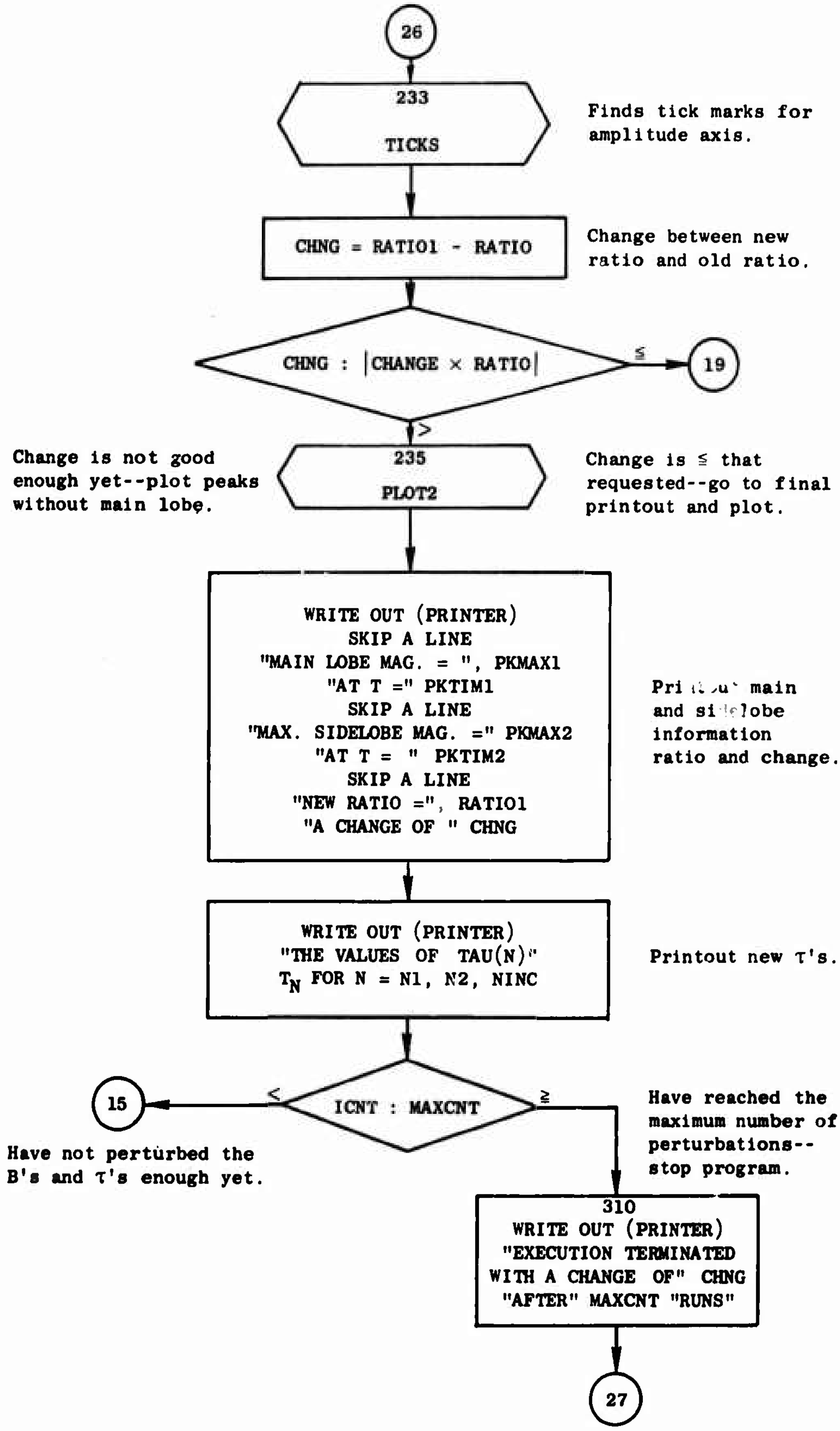

20
This section perturbs the τ's, tests them and plots intermediate plot. If within change requested, plots final plot and stops.
RATIO = RATIO1
Save new ratio.
IFLAG = 0
Now perturbing the τ's.
J1 = N1
Do the first tap outside the loop since may have to check against the min and max τ.
TAUT J1 = TAUP J1 + TAUINC
PROD : 0
≥
<
85
TAUINC : 0
<
=
>
90
TAUT J1 : TAUMIN
≥
<
100
TAUT J1 : TAUMAX
≤
>
95
TAUT J1 = TAUMIN
TAUT N1 not > TAUMAX or < TAUMIN
105
TAUT J1 = TAUMAX
Calculate a new set of peaks using new TAUT N1.
If better, PKCALC will make them a valid set.
110
PKCALC (TAUP J1, TAUT J1)
SENSE LIGHT 3 ON
Yes
No
The TAUT N1 was better than TAUP N1, changes have been made; go to the rest of the TAUT.
The original TAU was better. Try subtracting TAUINC.
115
TAUT J1 = TAUP J1 - TAUINC
SENSE LIGHT 3 OFF
22
21


22
PROD : 0
New TAUT_N1 does not need to be checked.
120
TAUINC : 0
135
TAUT_J1 : TAUMIN
125
TAUT_J1 : TAUMAX
140
TAUT_J1 = TAUMIN
Check TAUT_N1 so that not > TAUMAX or < TAUMIN
130
TAUT_J1 = TAUMAX
145
PKCALC(TAUP_J1,TAUT_J1)
Generate new peaks. If better, PKCALC will make changes.
21
150
J = N1P1
23
J1 = J
TAUT_J = TAUP_J + TAUINC
This loop perturbs the τ's from the second to the next to last. These are not checked against TAUMIN or TAUMAX, but the method is the same.
PKCALC(TAUP_J,TAUT_J)
24

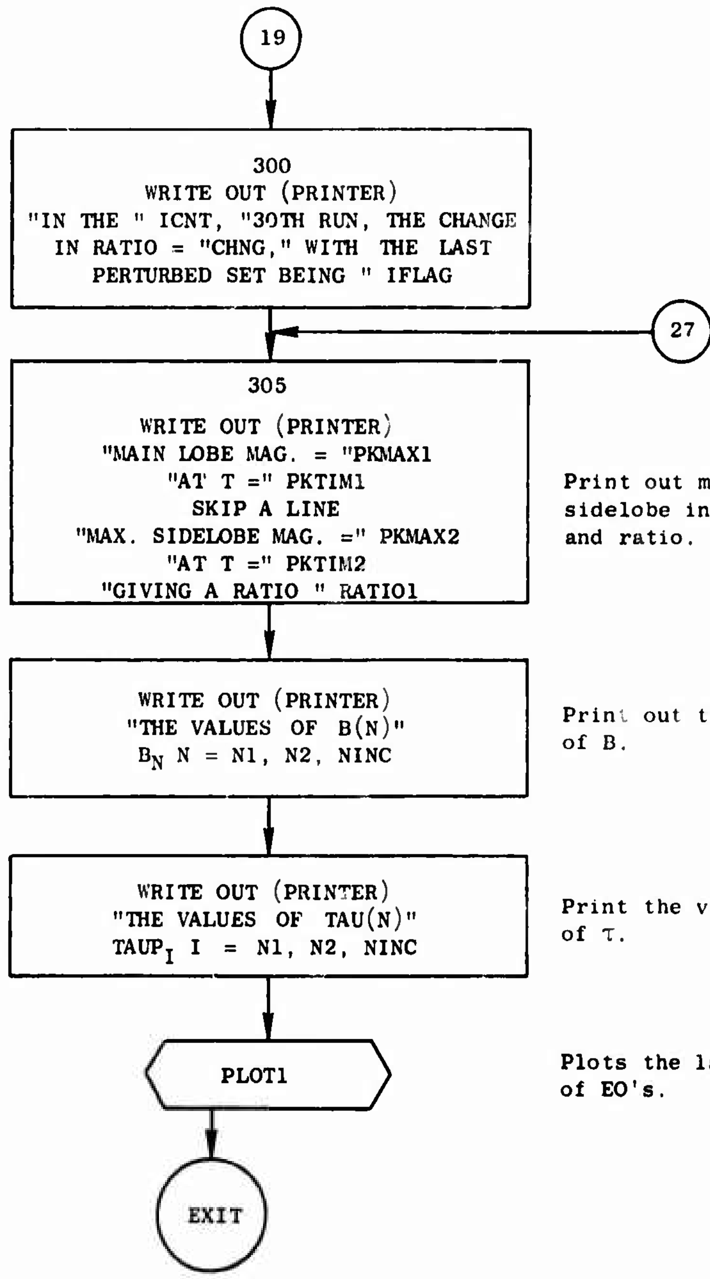


This section perturbs the last τ. Checks against TAUMAX and TAUMIN if necessary.


25
190
PKCALC (TAUP J1, TAUT J1)
SENSE LIGHT 3 ON
Yes
No
TURN SENSE LIGHT 3 OFF
195
TAUT J1 = TAUP J1 - TAUINC
PROD : 0
≥
<
200
TAUINC : 0
>
<
=
205
TAUT J1 : TAUMIN
≥
<
215
TAUT J1 : TAUMAX
≤
>
210
TAUT J1 = TAUMIN
220
TAUT J1 = TAUMAX
225
PKCALC (TAUP J1, TAUT J1)
230
AMPRNG = AMPC / PKMAX1
Scale factor for final plot.
RATIO1 : 10
<
≥
231
ARNG10 = AMPRNG
232
ARNG10 = 10AMPRNG
Scale factor for intermediate plot
26



26
233
TICKS
Finds tick marks for amplitude axis.
CHNG = RATIO1 - RATIO
Change between new ratio and old ratio.
CHNG : |CHANGE × RATIO|
≤
19
>
Change is not good enough yet--plot peaks without main lobe.
235
PLOT2
Change is ≤ that requested--go to final printout and plot.
WRITE OUT (PRINTER)
SKIP A LINE
"MAIN LOBE MAG. = ", PKMAX1
"AT T =" PKTIM1
SKIP A LINE
"MAX. SIDELOBE MAG. =" PKMAX2
"AT T = " PKTIM2
SKIP A LINE
"NEW RATIO =", RATIO1
"A CHANGE OF " CHNG
Printout main and sidelobe information ratio and change.
WRITE OUT (PRINTER)
"THE VALUES OF TAU(N)"
T_N FOR N = N1, N2, NINC
Printout new τ's.
15
<
ICNT : MAXCNT
≥
Have reached the maximum number of perturbations--stop program.
Have not perturbed the B's and τ's enough yet.
310
WRITE OUT (PRINTER)
"EXECUTION TERMINATED
WITH A CHANGE OF" CHNG
"AFTER" MAXCNT "RUNS"
27



Write out the last change in ratio and which set was last to be perturbed.

Print out main and sidelobe information and ratio.

Print out the values of B.

Print the values of τ.

Plots the last set of EO's.

APPENDIX B. FORTRAN PROGRAM LISTINGS

1. Input-Output Data

The input data for the FORTRAN program are tabulated below.

Card Number	Location (Columns)	Variable	Definition of Variable	Format
1	1-8	TMINI	Time to begin testing peak-to-sidelobe ratio	±xxxx.xx
	9-16	TMAXI	Time to stop testing peak-to-sidelobe ratio	"
	17-24	TINC	Time increment for all time variables	"
	25-32	TMINC	Initial value of time for plot purposes	"
	33-40	TMAXC	Final value of time for plot purposes	"
	41-48	TMINP	Initial value of plot time axis	"
2	1-8	TMAXP	Final value of plot time axis	"
	9-16	TLNGTH	Length of plot time axis (inches)	"
	17-24	TMAIN1	Beginning of time interval within which main lobe is determined	"
	25-32	TMAIN2	End of time interval begun by TMAIN1	"
	33-40	AMPLING	Height of amplitude axis in inches (≤10.00)	"

Card Number	Location (Columns)	Variable	Definition of Variable	Format
3	1-5	N1	Value of first n (integer)	xxxxx
	6-10	N2	Value of last n (integer)	"
	11-15	NINC	Spacing between n's (integer)	"
	16-20	ITAU	Boolean variable (0 if initial τ's are calculated, 1 if they are read as data)	"
	21-25	IB	Boolean variable (0 if initial B_n's are 0.5, 1 if they are read in)	"
	26-30	MAXCNT	Maximum number of times to run through τ_n, B_n set	"
4	1-14	TAUINC	Perturbation increment for τ's	±0.xxxxxxE±xx
	15-28	BINC	Perturbation increment for B's	"
	29-42	TAUMIN	Minimum allowable value for τ	"
	43-56	TAUMAX	Maximum allowable value for τ	"
	57-70	CHANGE	Change in peak-to-sidelobe ratio below which program will terminate	"
5	1-14	TAUP(1)	First τ (if ITAU = 1)	"
↓ K	(The τ's are arranged in increasing order of subscripts, five to a card, on as many cards as necessary to contain them. They are contained in columns 1-14, 15-28, 29-42, 43-56, and 57-70.)			
K+1	1-6	BP(1)	First B (if IB = 1)	+xxx.xxx
↓ Z	(The B's are arranged in increasing order of subscripts, ten to a card, in columns 1-6, 7-13, 14-20, 21-27, 28-34, 35-41, 42-48, 49-55, 56-62, and 63-69.)			

An outline of the output data for the FORTRAN program is given below.

a. Initial Case

(1) Printed Output

(a) Magnitude and time location of main lobe.

(b) Magnitude and time location of largest sidelobe.

(c) Initial values of τ's.

(d) Initial values of B's.

(2) Plotted Output

(a) The function r(t) is plotted from TMINP to TMAXP in intervals of TINC. The plot is contained within a box of length TLNGTH and height AMPLNG. The height of the main peak is scaled to 4.5 in.

(b) The function r(t) is plotted as above except the amplitude scale is increased $\times 10$ and the section from TMAIN1 to TMAIN2 is omitted.

b. Intermediate and Final Cases

(1) Printed Output

Same as initial except that the increase in peak-to-sidelobe ratio over the previous case is printed, and only the parameters (τ's or B's) perturbed on the last case are printed.

(2) Plotted Output

Same as initial case.

2. Program I

This program calculates the function

$$r(t) = \sum_{n=1}^{m} A(t-\tau_n)\, B_n \cos 2\pi \left[2(t-\tau_n) - 0.01(t-\tau_n)^2 + \phi\right]$$

for various values of ϕ. All values of B_n and τ_n must be read in as data, and the different values of ϕ must be inserted in the body of the program as PHI(). No flow chart is provided for this program due to its similarity to Program II. No perturbations are done--the function is calculated once and plotted. Subprograms required are ESUMII, A(T-TAU), PLOT1, AXPLOT, TICKS, as well as the three Stanford plot routines XYPLOT, XYLABL, and XYFRC.

```
      DIMENSION T(2501),TAUP(101),TAUT(101),BP(101),BT(101),EO(2501,2),
     1PKMAG(2000,2),PKTIM(2000,2),PKRAT(2000),ATICK(20),BTICK(20),
     2PHI(21)
      COMMON TMAXI,TINC,TR,TLNGTH,TRNGE,TLAG,LASTT,ITI2,ITM1,ITM2,
     1ITM1M1,ITM2P1,N1,N2,NINC,NPK,NPK1,NPK2,PKMAX1,PKMAX2,PKTIM1,
     2PKTIM2,IPERM,ITEMP,J1,IFLAG,AMPRNG,A1,A2,ARNG10,RATIO1,SPKMAX,
     3TZERO,T,TAUP,TAUT,BP,BT,EO,PKMAG,PKTIM,PKRAT,ATICK,BTICK,TL,TL1,
     4PHI,PHII
C READ IN BASIC TIME PARAMETERS, SET UP PLOTS AND INDEX PARAMETERS
      READ INPUT TAPE 5,500,TMINI,TMAXI,TINC,TMAIN1,TMAIN2,TLNGTH,AMPLNG
      TR=TMAXI-TMINI
      TL=1.0/TLNGTH
      TL1=TLNGTH+0.05
      TRNGE=1.0/TR
      TZERO=ABSF(TMINI)*TRNGE
      A1=5.0-0.5*AMPLNG
      A2=A1+AMPLNG
      AMPC=0.05*AMPLNG
      TLAG=MODF(TMINI,10.0)
      IF(TLAG)1,10,5
    1 TLAG=-TLAG
      GO TO 10
    5 TLAG=10.0-TLAG
   10 LASTT=0.1*TR+1.05
      ITI2=TR/TINC+1.5
      ITM1=(TMAIN1-TMINI)/TINC+1.5
      ITM2=(TMAIN2-TMINI)/TINC+1.5
      T(1)=TMINI
      DO 15 I=2,ITI2
   15 T(I)=T(I-1)+TINC
      ITM1M1=ITM1-1
      ITM2P1=ITM2+1
      ICNT=0
C READ IN REMAINING PARAMETERS, SET UP TAU AND B
      READ INPUT TAPE 5,510,N1,N2,NINC
      N1P1=N1+NINC
      N2M1=N2-1
   20 READ INPUT TAPE 5,520,(TAUP(I),I=N1,N2,NINC)
   40 READ INPUT TAPE 5,530,(BP(I),I=N1,N2,NINC)
      WRITE OUTPUT TAPE 6,620,(BP(I),I=N1,N2,NINC)
      WRITE OUTPUT TAPE 6,610,(TAUP(I),I=N1,N2,NINC)
      NPHI = 10
      PHI(1) = 0.10480
      PHI(2) = 0.15011
      PHI(3) = 0.01536
      PHI(4) = 0.02011
      PHI(5) = 0.81647
      PHI(6) = 0.91646
      PHI(7) = 0.69179
      PHI(8) = 0.14194
      PHI(9) = 0.62590
      PHI(10) = 0.36207
C CALCULATE INITIAL SUMS, GENERATE INITIAL PLOTS AND SIDE LOBE STRUCTURE
      DO 315 K=1,NPHI
```

```
      PHII = PHI(K)
   47 NPK=0
      EO(1,1)=ESJM(T(1))
      EO(2,1)=ESJM(T(2))
      IF(ABSF(EO(2,1))-ABSF(EO(1,1)))52,51,51
   51 PKMAX2=ABSF(EO(2,1))
      PKTIM2=T(2)
      GO TO 53
   52 PKMAX2=ABSF(EO(1,1))
      PKTIM2=T(1)
   53 PRES=EO(2,1)-EO(1,1)
      SENSE LIGHT 4
      I1=3
      I2=ITM1M1
   54 DO 75 I=I1,I2
      IM1=I-1
      PREV=PRES
      EO(I,1)=ESJM(T(I))
      PRES=EO(I,1)-EO(IM1,1)
      IF(PREV*PRES)55,55,75
   55 NPK=NPK+1
      PKMAG(NPK,1)=EO(IM1,1)
      PKTIM(NPK,1)=T(IM1)
      SAVE=ABSF(PKMAG(NPK,1))
      IF(SAVE-PKMAX2)75,70,70
   70 PKMAX2=SAVE
      PKTIM2=T(IM1)
   75 CONTINUE
      IF(SENSE LIGHT 4)77,82
   77 SPKMAX=EO(ITM1M1,1)
      PKMAX1=ABSF(SPKMAX)
      PKTIM1=T(ITM1M1)
      NPK1=NPK
      DO 80 I=ITM1,ITM2
      IM1=I-1
      PREV=PRES
      EO(I,1)=ESJM(T(I))
      PRES=EO(I,1)-EO(IM1,1)
      IF(PREV*PRES)78,78,80
   78 NPK=NPK+1
      PKMAG(NPK,1)=EO(IM1,1)
      PKTIM(NPK,1)=T(IM1)
      SAVE=ABSF(EO(IM1,1))
      IF(SAVE-PKMAX1)80,79,79
   79 PKMAX1=SAVE
      PKTIM1=T(IM1)
      SPKMAX=EO(IM1,1)
   80 CONTINUE
      I1=ITM2P1
      I2=ITI2
      NPK2=NPK+1
      GO TO 54
   82 IPERM=1
      ITEMP=2
      RATIO1=PKMAX1/PKMAX2
      AMPRNG=AMPC/PKMAX1
      IF(RATIO1-10.0)1000,1001,1001
 1000 ARNG10=AMPRNG
      GO TO 1002
 1001 ARNG10=10.0*AMPRNG
 1002 WRITE OUTPUT TAPE 6,605,PKMAX1,PKTIM1,PKMAX2,PKTIM2,RATIO1
      CALL TICKS
      CALL PLOT1
  315 CONTINUE
```

```
500 FORMAT(7F8.2)
510 FORMAT(3I5)
520 FORMAT(5E14.6)
530 FORMAT(10F6.3)
605 FORMAT(18HOMAIN LOBE MAG. = ,E15.8,2X,7HAT T = ,F8.3/23HOMAX. SIDE
   1 LOBE MAG. = ,E15.8,2X,7HAT T = ,F8.3,5X,17HGIVING A RATIO = ,E15.
   28)
610 FORMAT(21HOTHE VALUES OF TAU(N)/(10E13.6))
620 FORMAT(19HOTHE VALUES OF B(N)/(20F6.3))
625 FORMAT(I4)
630 FORMAT(10F8.5)
    CALL EXIT
    END
```

3. Program II

This is the general peak-to-sidelobe ratio optimizing program. The function calculated is

$$r(t) = \sum_{n=1}^{m} A(t-\tau_n)\, B_n \cos 2\pi\left[2(t-\tau_n) - 0.01(t-\tau_n)^2\right]$$

The initial values of B_n must be read in as data, and the initial values of τ_n are calculated by Subprogram TAUN. The region of the main peak is TMAIN1 $< t <$ TMAIN2, and the sidelobe is considered the largest peak outside this region. This program will terminate when a series of perturbations results in an improvement of the peak-to-sidelobe ratio less than CHANGE. Subprograms required are ESUMI, A(T-TAU), PLOT1, PLOT2, AXPLOT, TICKS, XYPLOT, XYLABL, and XYFRC.

```
      DIMENSION T(2501),TAUP(101),TAUT(101),BP(101),BT(101),EO(2501,2),
     1PKMAG(2000,2),PKTIM(2000,2),PKRAT(2000),ATICK(20),BTICK(20)
      COMMON TMAXI,TINC,TR,TLNGTH,TRNGE,TLAG,LASTT,ITI2,ITM1,ITM2,
     1ITM1M1,ITM2P1,N1,N2,NINC,NPK,NPK1,NPK2,PKMAX1,PKMAX2,PKTIM1,
     2PKTIM2,IPERM,ITEMP,J1,IFLAG,AMPRNG,A1,A2,ARNG10,RATIO1,SPKMAX,
     3TZERO,T,TAUP,TAUT,BP,BT,EO,PKMAG,PKTIM,PKRAT,ATICK,BTICK,TL,TL1
C READ IN BASIC TIME PARAMETERS, SET UP PLOTS AND INDEX PARAMETERS
      READ INPUT TAPE 5,500,TMINI,TMAXI,TINC,TMAIN1,TMAIN2,TLNGTH,AMPLNG
      TR=TMAXI-TMINI
      TL=1.0/TLNGTH
      TL1=TLNGTH+0.05
      TRNGE=1.0/TR
      TZERO=ABSF(TMINI)*TRNGE
      A1=5.0-0.5*AMPLNG
      A2=A1+AMPLNG
      AMPC=0.05*AMPLNG
      TLAG=MODF(TMINI,10.0)
      IF(TLAG)1,10,5
```

```
    1 TLAG=-TLAG
      GO TO 10
    5 TLAG=10.0-TLAG
   10 LASTT=0.1*TR+1.05
      ITI2=TR/TINC+1.5
      ITM1=(TMAIN1-TMINI)/TINC+1.5
      ITM2=(TMAIN2-TMINI)/TINC+1.5
      T(1)=TMINI
      DO 15 I=2,ITI2
   15 T(I)=T(I-1)+TINC
      ITM1M1=ITM1-1
      ITM2P1=ITM2+1
      ICNT=0
C READ IN REMAINING PARAMETERS, SET UP TAU AND B
      READ INPUT TAPE 5,510,N1,N2,NINC,ITAU,IB,MAXCNT,TAUINC,BINC,TAUMIN
     1,TAUMAX,CHANGE
      N1P1=N1+NINC
      N2M1=N2-1
      IF(ITAU)20,25,20
   20 READ INPUT TAPE 5,520,(TAUP(I),I=N1,N2,NINC)
      GO TO 35
   25 DO 30 I=N1,N2,NINC
      FLI=I
      TAUP(I)=TAU(FLI)
   30 CONTINUE
   35 PROD=TAUINC*(TAUP(N2)-TAUP(N1))
      IF(IB)40,45,40
   40 READ INPUT TAPE 5,530,(BP(I),I=N1,N2,NINC)
      GO TO 47
   45 DO 46 I=N1,N2,NINC
   46 BP(I)=0.5
C CALCULATE INITIAL SUMS, GENERATE INITIAL PLOTS AND SIDE LOBE STRUCTURE
   47 NPK=0
      EO(1,1)=ESUM(T(1))
      EO(2,1)=ESUM(T(2))
      IF(ABSF(EO(2,1))-ABSF(EO(1,1)))52,51,51
   51 PKMAX2=ABSF(EO(2,1))
      PKTIM2=T(2)
      GO TO 53
   52 PKMAX2=ABSF(EO(1,1))
      PKTIM2=T(1)
   53 PRES=EO(2,1)-EO(1,1)
      SENSE LIGHT 4
      I1=3
      I2=ITM1M1
   54 DO 75 I=I1,I2
      IM1=I-1
      PREV=PRES
      EO(I,1)=ESUM(T(I))
      PRES=EO(I,1)-EO(IM1,1)
      IF(PREV*PRES)55,55,75
   55 NPK=NPK+1
      PKMAG(NPK,1)=EO(IM1,1)
      PKTIM(NPK,1)=T(IM1)
      SAVE=ABSF(PKMAG(NPK,1))
      IF(SAVE-PKMAX2)75,70,70
   70 PKMAX2=SAVE
      PKTIM2=T(IM1)
   75 CONTINUE
      IF(SENSE LIGHT 4)77,82
   77 SPKMAX=EO(ITM1M1,1)
      PKMAX1=ABSF(SPKMAX)
      PKTIM1=T(ITM1M1)
      NPK1=NPK
```

```
      DO 80 I=ITM1,ITM2
      IM1=I-1
      PREV=PRES
      EO(I,1)=ESUM(T(I))
      PRES=EO(I,1)-EO(IM1,1)
      IF(PREV*PRES)78,78,80
   78 NPK=NPK+1
      PKMAG(NPK,1)=EO(IM1,1)
      PKTIM(NPK,1)=T(IM1)
      SAVE=ABSF(EO(IM1,1))
      IF(SAVE-PKMAX1)80,79,79
   79 PKMAX1=SAVE
      PKTIM1=T(IM1)
      SPKMAX=EO(IM1,1)
   80 CONTINUE
      I1=ITM2P1
      I2=ITI2
      NPK2=NPK+1
      GO TO 54
   82 IPERM=1
      ITEMP=2
      RATIO1=PKMAX1/PKMAX2
      AMPRNG=AMPC/PKMAX1
      IF(RATIO1-10.0)1000,1001,100.
 1000 ARNG10=AMPRNG
      GO TO 1002
 1001 ARNG10=10.0*AMPRNG
 1002 WRITE OUTPUT TAPE 6,600
      WRITE OUTPUT TAPE 6,605,PKMAX1,PKTIM1,PKMAX2,PKTIM2,RATIO1
      WRITE OUTPUT TAPE 6,620,(BP(I),I=N1,N2,NINC)
      WRITE OUTPUT TAPE 6,610,(TAUP(I),I=N1,N2,NINC)
      CALL TICKS
      CALL PLOT1
C THE NEXT SECTION PERMUTES ALL B(N), ONE AT A TIME, TESTS FOR ANY
C IMPROVEMENT, PLOTS IMPROVEMENT, PRINTS OUT NEW B(N)
   84 RATIO=RATIO1
      ICNT=ICNT+1
      IFLAG=1
      DO 290 J=N1,N2,NINC
      J1=J
      BT(J)=BP(J)+BINC
      IF(BINC)240,260,250
  240 IF(BT(J))245,260,260
  245 BT(J)=0.0
      GO TO 260
  250 IF(BT(J)-1.0)260,260,255
  255 BT(J)=1.0
  260 CALL PKCALC(BP(J),BT(J))
      IF(SENSE LIGHT 3)290,265
  265 BT(J)=BP(J)-BINC
      IF(BINC)270,285,280
  270 IF(BT(J)-1.0)285,285,275
  275 BT(J)=1.0
      GO TO 285
  280 IF(BT(J))282,285,285
  282 BT(J)=0.0
  285 CALL PKCALC(BP(J),BT(J))
  290 CONTINUE
      AMPRNG=AMPC/PKMAX1
      IF(RATIO1-10.0)291,292,292
  291 ARNG10=AMPRNG
      GO TO 293
  292 ARNG10=10.0*AMPRNG
  293 CALL TICKS
```

```
      CHNG=RATIO1-RATIO
      IF(CHNG-ABSF(CHANGE*RATIO))300,300,295
  295 CALL PLOT2
      WRITE OUTPUT TAPE 6,650,PKMAX1,PKTIM1,PKMAX2,PKTIM2,RATIO1,CHNG
      WRITE OUTPUT TAPE 6,620,(BP(I),I=N1,N2,NINC)
C THE NEXT SECTION PERMUTES ALL TAU(N), ONE AT A TIME, TESTS FOR ANY
C IMPROVEMENT, PLOTS IMPROVEMENT, PRINTS OUT NEW TAU(N)
      RATIO=RATIO1
      IFLAG=0
      J1=N1
      TAUT(J1)=TAUP(J1)+TAUINC
      IF(PROD)85,110,110
   85 IF(TAUINC)90,110,100
   90 IF(TAUT(J1)-TAUMIN)95,110,110
   95 TAUT(J1)=TAUMIN
      GO TO 110
  100 IF(TAUT(J1)-TAUMAX)110,110,105
  105 TAUT(J1)=TAUMAX
  110 CALL PKCALC(TAUP(J1),TAUT(J1))
      IF(SENSE LIGHT 3)150,115
  115 TAUT(J1)=TAUP(J1)-TAUINC
      IF(PROD)145,145,120
  120 IF(TAUINC)125,145,135
  125 IF(TAUT(J1)-TAUMAX)145,145,130
  130 TAUT(J1)=TAUMAX
      GO TO 145
  135 IF(TAUT(J1)-TAUMIN)140,145,145
  140 TAUT(J1)=TAUMIN
  145 CALL PKCALC(TAUP(J1),TAUT(J1))
  150 DO 160 J=N1P1,N2M1,NINC
      J1=J
      TAUT(J)=TAUP(J)+TAUINC
      CALL PKCALC(TAUP(J),TAUT(J))
      IF(SENSE LIGHT 3)160,155
  155 TAUT(J)=TAUP(J)-TAUINC
      CALL PKCALC(TAUP(J),TAUT(J))
  160 CONTINUE
      J1=N2
      TAUT(J1)=TAUP(J1)+TAUINC
      IF(PROD)190,190,165
  165 IF(TAUINC)180,190,170
  170 IF(TAUT(J1)-TAUMAX)190,190,175
  175 TAUT(J1)=TAUMAX
      GO TO 190
  180 IF(TAUT(J1)-TAUMIN)185,190,190
  185 TAUT(J1)=TAUMIN
  190 CALL PKCALC(TAUP(J1),TAUT(J1))
      IF(SENSE LIGHT 3)230,195
  195 TAUT(J1)=TAUP(J1)-TAUINC
      IF(PROD)200,225,225
  200 IF(TAUINC)215,225,205
  205 IF(TAUT(J1)-TAUMIN)210,225,225
  210 TAUT(J1)=TAUMIN
      GO TO 225
  215 IF(TAUT(J1)-TAUMAX)225,225,220
  220 TAUT(J1)=TAUMAX
  225 CALL PKCALC(TAUP(J1),TAUT(J1))
  230 AMPRNG=AMPC/PKMAX1
      IF(RATIO1-10.0)231,232,232
  231 ARNG10=AMPRNG
      GO TO 233
  232 ARNG10=10.0*AMPRNG
  233 CALL TICKS
      CHNG=RATIO1-RATIO
      IF(CHNG-ABSF(CHANGE*RATIO))300,300,235
```

```
235 CALL PLOT2
    WRITE OUTPUT TAPE 6,650,PKMAX1,PKTIM1,PKMAX2,PKTIM2,RATIO1,CHNG
    WRITE OUTPUT TAPE 6,610,(TAUP(I),I=N1,N2,NINC)
    IF(ICNT-MAXCNT)84,310,310
300 WRITE OUTPUT TAPE 6,630,ICNT,CHNG,IFLAG
305 WRITE OUTPUT TAPE 6,605,PKMAX1,PKTIM1,PKMAX2,PKTIM2,RATIO1
    WRITE OUTPUT TAPE 6,620,(BP(I),I=N1,N2,NINC)
    WRITE OUTPUT TAPE 6,610,(TAUP(I),I=N1,N2,NINC)
    CALL PLOT1
    GO TO 315
310 WRITE OUTPUT TAPE 6,640,CHNG,MAXCNT
    GO TO 305
315 CONTINUE
500 FORMAT(7F8.2)
510 FORMAT(6I5/5E14.6)
520 FORMAT(5E14.6)
530 FORMAT(10F6.3)
600 FORMAT(48H1INITIAL CALCULATIONS GIVE THE FOLLOWING RESULTS/)
605 FORMAT(18H0MAIN LOBE MAG. = ,E15.8,2X,7HAT T = ,F8.3/23H0MAX. SIDE
   1 LOBE MAG. = ,E15.8,2X,7HAT T = ,F8.3,5X,17HGIVING A RATIO = ,E15.
   28)
610 FORMAT(21H0THE VALUES OF TAU(N)/(10E13.6))
620 FORMAT(19H0THE VALUES OF B(N)/(20F6.3))
630 FORMAT(7H0IN THE,I5,30HTH RUN, THE CHANGE IN RATIO = ,E13.6,34HWIT
   1H THE LAST PERTURBED SET BEING ,I1)
640 FORMAT(39H0EXECUTION TERMINATED WITH A CHANGE OF ,E13.6,5X,6HAFTER
   1 ,I5,2X,4HRUNS)
650 FORMAT(1H0/18H0MAIN LOBE MAG. = ,E15.8,2X,7HAT T = ,F8.3/
   123H MAX. SIDE LOBE MAG. = ,E15.8,2X,7HAT T = ,F8.3/13H NEW RATIO =
   2 ,E13.6,5X,12HA CHANGE OF ,E13.6)
    CALL EXIT
    END(1,0,0,0,0,0,1,0,0,0,0,0,0,0,0)
```

4. <u>Subprogram ESUMI</u>

The following function is written as a subprogram to allow changes in the scan rate and the initial frequency to be made without the need to recompile the main program:

$$\text{ESUMI} = \sum_{n=1}^{m} A(T-\tau_n)\, B_n \cos\left\{2\pi\left[2(T-\tau_n) - 0.01(T-\tau_n)^2\right]\right\}$$

where T is the current value of t in the main program.

```
  ESUM   SUBPROGRAM TO CALCULATE SUM OF COSINES

      FUNCTION ESUM(TIME)
      DIMENSION T(2501),TAUP(101),TAUT(101),BP(101),BT(101),EO(2501,2),
     1PKMAG(2000,2),PKTIM(2000,2),PKRAT(2000),ATICK(20),BTICK(20)
      COMMON TMAXI,TINC,TR,TLNGTH,TRNGE,TLAG,LASTT,ITI2,ITM1,ITM2,
     1ITM1M1,ITM2P1,N1,N2,NINC,NPK,NPK1,NPK2,PKMAX1,PKMAX2,PKTIM1,
     2PKTIM2,IPERM,ITEMP,J1,IFLAG,AMPRNG,A1,A2,ARNG10,RATIO1,SPKMAX,
     3TZERO,T,TAUP,TAUT,BP,BT,EO,PKMAG,PKTIM,PKRAT,ATICK,BTICK,TL,TL1
```

```
      ESUM=0.0
      DO 10 J=N1,N2,NINC
      TMTAU=TIME-TAUP(J)
      ESUM=ESUM+BP(J)*A(TMTAU)*COSF(6.2831853*(2.0*TMTAU-0.01*TMTAU*
     1TMTAU))
   10 CONTINUE
      RETURN
      END(1,0,0,0,0,0,1,0,0,0,0,0,0,0,0)
```

5. Subprogram ESUMII

ESUMII differs from ESUMI by the addition of a phase term to the cosine argument. The function calculated is

$$\text{ESUMII} = \sum_{n=1}^{m} A(T-\tau_n)\, B_n \cos\left\{2\pi\left[2(T-\tau_n) - 0.01(T-\tau_n)^2 + \text{PHII}\right]\right\}$$

where T is the current value of t in the main program and PHII is a phase term obtained from the main program. ESUMII can only be used with Program I.

```
  ESUM  SUBROUTINE TO CALCULATE INITIAL FUNCTION

      FUNCTION ESUM(TIME)
      DIMENSION T(2501),TAUP(101),TAUT(101),BP(101),BT(101),E0(2501,2),
     1PKMAG(2000,2),PKTIM(2000,2),PKRAT(2000),ATICK(20),BTICK(20),
     2PHI(21)
      COMMON TMAXI,TINC,TR,TLNGTH,TRNGE,TLAG,LASTT,IT12,ITM1,ITM2,
     1ITM1M1,ITM2P1,N1,N2,NINC,NPK,NPK1,NPK2,PKMAX1,PKMAX2,PKTIM1,
     2PKTIM2,IPERM,ITEMP,J1,IFLAG,AMPRNG,A1,A2,ARNG10,RATIO1,SPKMAX,
     3TZERO,T,TAUP,TAUT,BP,BT,E0,PKMAG,PKTIM,PKRAT,ATICK,BTICK,TL,TL1,
     4PHI,PHII
      ESUM=0.0
      DO 10 J=N1,N2,NINC
      TMTAU=TIME-TAUP(J)
      B1=BP(J)*A(TMTAU)
      B2=2.0*TMTAU-0.01*TMTAU*TMTAU
      ESUM=ESUM+B1*COSF(6.2831853*(B2+PHII))
   10 CONTINUE
      RETURN
      END(1,0,0,0,0,0,1,0,0,0,0,0,0,0,0)
```

6. Subprogram EREV

After a perturbation of B or τ has been made, EREV calculates the new value of $r(t)$ for all values of t in the main program. The new value is

$$r(t) = r_o(t) + A\left(t-\tau_i^1\right) B_i^1 \cos\left\{2\pi\left[2\left(t-\tau_i^1\right) - 0.01\left(t-\tau_i^1\right)^2\right]\right\}$$

$$- A(t-\tau_i)\, B_i \cos\left\{2\pi\left[2(t-\tau_i) - 0.01(t-\tau_i)^2\right]\right\}$$

where $r_o(t)$ is the value of

$$\sum_{i=1}^{m} r_n(t) = r(t)$$

before the perturbation. The change in $r(t)$ due to the change in the i^{th} tap is calculated by subtracting the initial contributions from the i^{th} tap from $r_o(t)$ and adding the new contributions. This must be done for each value of t.

```
C  EREV SUBROUTINE TO REVISE FUNCTION
      SUBROUTINE EREV
      DIMENSION T(2501),TAUP(101),TAUT(101),BP(101),BT(101),EO(2501,2),
     1PKMAG(2000,2),PKTIM(2000,2),PKRAT(2000),ATICK(20),BTICK(20)
      COMMON TMAXI,TINC,TR,TLNGTH,TRNGE,TLAG,LASTT,ITI2,ITM1,ITM2,
     1ITM1M1,ITM2P1,N1,N2,NINC,NPK,NPK1,NPK2,PKMAX1,PKMAX2,PKTIM1,
     2PKTIM2,IPERM,ITEMP,J1,IFLAG,AMPRNG,A1,A2,ARNG10,RATIO1,SPKMAX,
     3TZERO,T,TAUP,TAUT,BP,BT,EO,PKMAG,PKTIM,PKRAT,ATICK,BTICK,TL,TL1
      B1=BP(J1)
      TAU1=TAUP(J1)
      IF(IFLAG)5,5,10
    5 B2=B1
      TAU2=TAUT(J1)
      GU TO 15
   10 B2=BT(J1)
      TAU2=TAU1
   15 DO 20 II=1,ITI2
      TMTAU1=T(II)-TAU1
      TMTAU2=T(II)-TAU2
      EO(II,ITEMP)=EO(II,IPERM)-B1*A(TMTAU1)*COSF(6.2831853*(2.0*TMTAU1-
     10.0100*TMTAU1*TMTAU1))+B2*A(TMTAU2)*COSF(6.2831853*(2.0*TMTAU2-
     20.0100*TMTAU2*TMTAU2))
   20 CONTINUE
      RETURN
      END
```

7. Subprogram TAUN

If ITAU = 0, then this subprogram is called. It calculates the values of τ which will cause the contributions from all taps to add in phase at $t = 50$ sec as described in Eq. (5). The function calculated is

$$TAU = 100.0\sqrt{1.01 - (0.01)FLN} - 50.0$$

where FLN is a floating point N.

```
TAUN     SUBPROGRAM TO CALCULATE TAU AS A FUNCTION OF N

         FUNCTION TAU(FLN)
         TAU=100.0*SQRTF(1.01-0.01*FLN)-50.0
         RETURN
         END(1,0,0,0,0,0,1,0,0,0,0,0,0,0,0)
```

8. Subprogram AN

This subprogram calculates the values of $A(t-\tau_n)$.

$$A(t-\tau_n) = \begin{cases} \left(\dfrac{t-\tau_n-25}{35}\right)^2 & -10 \leq (t-\tau_n) \leq 60 \\ 0 & -10 > (t-\tau_n) > 60 \end{cases}$$

```
AN       SUBPROGRAM TO CALCULATE A AS A FUNCTION OF T-TAU(N)

         FUNCTION A(TMTAU)
         IF(TMTAU+10.0)15,10,5
       5 IF(TMTAU-60.0)10,10,15
      10 A=1.0-.81632653E-3*(TMTAU-25.0)*(TMTAU-25.0)
         RETURN
      15 A=0.0
         RETURN
         END(1,0,0,0,0,0,1,0,0,0,0,0,0,0,0)
```

9. Subprogram PLOT1

PLOT1 is a subprogram which plots $r(t)$ using Subprograms XYPLOT, XYLABL, and XYFRC. The largest peak of $r(t)$ is scaled to 4.5 in. which places $r(t) = 0$ along the center of the plot. PLOT1 calls PLOT2 before returning to the main program.

```
PLOT1    SUBPROGRAM TO PLOT INITIAL AND FINAL DATA

      SUBROUTINE PLOT1
      DIMENSION T(2501),TAUP(101),TAUT(101),BP(101),BT(101),EO(2501,2),
     1PKMAG(2000,2),PKTIM(2000,2),PKRAT(2000),ATICK(20),BTICK(20)
      COMMON TMAXI,TINC,TR,TLNGTH,TRNGE,TLAG,LASTT,ITI2,ITM1,ITM2,
     1ITM1M1,ITM2P1,N1,N2,NINC,NPK,NPK1,NPK2,PKMAX1,PKMAX2,PKTIM1,
     2PKTIM2,IPERM,ITEMP,J1,IFLAG,AMPRNG,A1,A2,ARNG10,RATIO1,SPKMAX,
     3TZERO,T,TAUP,TAUT,BP,BT,EO,PKMAG,PKTIM,PKRAT,ATICK,BTICK,TL,TL1
      CALL AXPLOT(AMPRNG)
      CALL XYPLOT(T(1),EO(1,IPERM),TRNGE,AMPRNG,TZERO,0.5,TLNGTH,3)
      DO 20 I=2,ITI2
      CALL XYPLOT(T(I),EO(I,IPERM),TRNGE,AMPRNG,TZERO,0.5,TLNGTH,2)
   20 CONTINUE
  140 CALL XYFRC
      CALL XYPLOT(1.0,0.0,1.0,1.0,0.0,0.0,1.0,3)
      CALL XYFRC
      CALL PLOT2
      RETURN
      END(1,0,0,0,0,0,1,0,0,0,0,0,0,0,0)
```

10. Subprogram PLOT2

PLOT2 is the same as PLOT1 except that the largest peak is scaled to 45 in. instead of 4.5 in., and the region from TMAIN1 to TMAIN2 is not plotted.

```
PLOT2    SUBPROGRAM TO PLOT INTERMEDIATE DATA

      SUBROUTINE PLOT2
      DIMENSION T(2501),TAUP(101),TAUT(101),BP(101),BT(101),EO(2501,2),
     1PKMAG(2000,2),PKTIM(2000,2),PKRAT(2000),ATICK(20),BTICK(20)
      COMMON TMAXI,TINC,TR,TLNGTH,TRNGE,TLAG,LASTT,ITI2,ITM1,ITM2,
     1ITM1M1,ITM2P1,N1,N2,NINC,NPK,NPK1,NPK2,PKMAX1,PKMAX2,PKTIM1,
     2PKTIM2,IPERM,ITEMP,J1,IFLAG,AMPRNG,A1,A2,ARNG10,RATIO1,SPKMAX,
     3TZERO,T,TAUP,TAUT,BP,BT,EO,PKMAG,PKTIM,PKRAT,ATICK,BTICK,TL,TL1
      CALL AXPLOT(ARNG10)
      CALL XYPLOT(T(1),EO(1,IPERM),TRNGE,ARNG10,TZERO,0.5,TLNGTH,3)
      DO 10 L=1,NPK1
      CALL XYPLOT(PKTIM(L,IPERM),PKMAG(L,IPERM),TRNGE,ARNG10,TZERO,0.5,
     1TLNGTH,2)
   10 CONTINUE
      ET1=EO(ITM1M1,IPERM)
      ET2=EO(ITM2P1,IPERM)
      ET3=ET1*ARNG10+0.
      ET4=ET2*ARNG10+0.5
      WRITE OUTPUT TAPE 6,2000,PKTIM(NPK1,IPERM),PKMAG(NPK1,IPERM),
```

```
      1T(ITM1M1),ET1,ET3,T(ITM2P1),ET2,ET4,PKTIM(NPK2,IPERM),
      2PKMAG(NPK2,IPERM)
 2000 FORMAT(10E12.4)
       IF(ET3-1.0)12,12,14
    12 CALL XYPLOT(T(ITM1M1),ET1,TRNGE,ARNG10,TZERO,0.5,TLNGTH,2)
    14 IF(ET4-1.0)16,16,18
    16 CALL XYPLOT(T(ITM2P1),ET2,TRNGE,ARNG10,TZERO,0.5,TLNGTH,3)
       GO TO 19
    18 CALL XYPLOT(PKTIM(NPK2,IPERM),PKMAG(NPK2,IPERM),TRNGE,ARNG10,
      1TZERO,0.5,TLNGTH,3)
    19 DO 20 L=NPK2,NPK
       CALL XYPLOT(PKTIM(L,IPERM),PKMAG(L,IPERM),TRNGE,ARNG10,TZERO,0.5,
      1TLNGTH,2)
    20 CONTINUE
       CALL XYPLOT(T(ITI2),EO(ITI2,IPERM),TRNGE,ARNG10,TZERO,0.5,
      1TLNGTH,2)
       CALL XYFRC
       CALL XYPLOT(1.0,0.0,1.0,1.0,0.0,0.0,1.0,3)
       CALL XYFRC
       RETURN
       END(1,0,0,0,0,0,1,0,0,0,0,0,0,0,0)
```

11. Subprogram PKCALC

This subprogram evaluates the new set of maxima and minima after a perturbation has been made. If an improvement in the peak-to-sidelobe ratio has been made, PKCALC returns to the main program and leaves the variable changed. If no improvement is found, the sign of the perturbation is changed and the peak-to-sidelobe ratio is again calculated. As before, an improvement will return control to the main program; if no improvement is obtained, the variable is returned to its original value before control is returned to the main program.

```
PKCALC   SUBPROGRAM TO CALCULATE NEW SET OF PEAKS AND EVALUATE THEM

       SUBROUTINE PKCALC(AP,AT)
       DIMENSION T(2501),TAUP(101),TAUT(101),BP(101),BT(101),EO(2501,2),
      1PKMAG(2000,2),PKTIM(2000,2),PKRAT(2000),ATICK(20),BTICK(20)
       COMMON TMAXI,TINC,IR,TLNGTH,TRNGE,TLAG,LASTT,ITI2,ITM1,ITM2,
      1ITM1M1,ITM2P1,N1,N2,NINC,NPK,NPK1,NPK2,PKMAX1,PKMAX2,PKTIM1,
      2PKTIM2,IPERM,ITEMP,J1,IFLAG,AMPRNG,A1,A2,ARNG10,RATIO1,SPKMAX,
      3TZERO,T,TAUP,TAUT,BP,BT,EO,PKMAG,PKTIM,PKRAT,ATICK,BTICK,TL,TL1
       IF(SENSE LIGHT 3)5,5
     5 NOPKS=0
       CALL EREV
       PRES=EO(2,ITEMP)-EO(1,ITEMP)
       IF(ABSF(EO(2,ITEMP))-ABSF(EO(1,ITEMP)))7,6,6
     6 TPMAX2=ABSF(EO(2,ITEMP))
       TPTIM2=T(2)
       GO TO 8
     7 TPMAX2=ABSF(EO(1,ITEMP))
       TPTIM2=T(1)
```

```
  8 SENSE LIGHT 4
    I1=3
    I2=ITM1M1
  9 DO 29 I=I1,I2
    IM1=I-1
    PREV=PRES
    PRES=EO(I,ITEMP)-EO(IM1,ITEMP)
    IF(PREV*PRES)10,10,29
 10 NOPKS=NOPKS+1
    PKMAG(NOPKS,ITEMP)=EO(IM1,ITEMP)
    PKTIM(NOPKS,ITEMP)=T(IM1)
    SAVE=ABSF(PKMAG(NOPKS,ITEMP))
    IF(SAVE-TPMAX2)29,25,25
 25 TPMAX2=SAVE
    TPTIM2=T(IM1)
 29 CONTINUE
    IF(SENSE LIGHT 4)30,34
 30 STPMAX=EO(ITM1M1,ITEMP)
    TPMAX1=ABSF(STPMAX)
    TPTIM1=T(ITM1M1)
    NPKT1=NOPKS
    DO 33 I=ITM1,ITM2
    IM1=I-1
    PREV=PRES
    PRES=EO(I,ITEMP)-EO(IM1,ITEMP)
    IF(PREV*PRES)31,31,33
 31 NOPKS=NOPKS+1
    PKMAG(NOPKS,ITEMP)=EO(IM1,ITEMP)
    PKTIM(NOPKS,ITEMP)=T(IM1)
    SAVE=ABSF(PKMAG(NOPKS,ITEMP))
    IF(SAVE-TPMAX1)33,32,32
 32 TPMAX1=SAVE
    STPMAX=PKMAG(NOPKS,ITEMP)
    TPTIM1=T(IM1)
 33 CONTINUE
    I1=ITM2P1
    I2=ITI2
    NPKT2=NOPKS+1
    GO TO 9
 34 TRATIO=TPMAX1/TPMAX2
    IF(TRATIO-RATIO1)50,50,35
 35 PKMAX1=TPMAX1
    PKTIM1=TPTIM1
    PKMAX2=TPMAX2
    PKTIM2=TPTIM2
    RATIO1=TRATIO
    SPKMAX=STPMAX
    NPK=NOPKS
    NPK1=NPKT1
    NPK2=NPKT2
    AP=AT
    SENSE LIGHT 3
    IF(IPERM-1)40,40,45
 40 IPERM=2
    ITEMP=1
    GO TO 50
 45 IPERM=1
    ITEMP=2
 50 CONTINUE
    RETURN
    END(1,0,0,0,0,0,1,0,0,0,0,0,0,0,0)
```

12. Subprogram AXPLOT

This subprogram draws a box around the plot. AXPLOT is called by PLOT1 or PLOT2, and AXPLOT calls TICKS.

```
AXPLOT   SUBPROGRAM TO PLOT AXES FOR GRAPHS

      SUBROUTINE AXPLOT(ARNG)
      DIMENSION T(2501),TAUP(101),TAUT(101),HP(101),BT(101),EO(2501,2),
     1PKMAG(2000,2),PKTIM(2000,2),PKRAT(2000),ATICK(20),BTICK(20)
      COMMON TMAXI,TINC,TR,TLNGTH,TRNGE,TLAG,LASTT,ITI2,ITM1,ITM2,
     1ITM1M1,ITM2P1,N1,N2,NINC,NPK,NPK1,NPK2,PKMAX1,PKMAX2,PKTIM1,
     2PKTIM2,IPERM,ITEMP,J1,IFLAG,AMPRNG,A1,A2,ARNG10,RATIO1,SPKMAX,
     3TZERO,T,TAUP,TAUT,BP,BT,EO,PKMAG,PKTIM,PKRAT,ATICK,BTICK,TL,TL1
      CALL XYPLOT(1.0,0.0,1.0,1.0,0.0,0.0,1.0,3)
      CALL XYFRC
      CALL XYPLOT(0.0,0.0,TRNGE,0.1,0.0,0.5,TLNGTH,3)
      T1=TLAG-10.0
      DO 10 L=1,LASTT
      T1=T1+10.0
      CALL XYPLOT(T1,0.0,TRNGE,0.1,0.0,0.5,TLNGTH,2)
      CALL XYPLOT(T1,0.05,TRNGE,0.1,0.0,0.5,TLNGTH,2)
      CALL XYPLOT(T1,-0.05,TRNGE,0.1,0.0,0.5,TLNGTH,2)
      CALL XYPLOT(T1,0.0,TRNGE,0.1,0.0,0.5,TLNGTH,2)
   10 CONTINUE
      CALL XYPLOT(TR,0.0,TRNGE,0.1,0.0,0.5,TLNGTH,2)
      CALL XYPLOT(0.0,A1,1.0,0.1,0.0,0.0,TLNGTH,3)
      DO 15 L=1,10
      CALL XYPLOT(0.0,ATICK(L),TL,ARNG,0.0,0.5,TLNGTH,2)
      CALL XYPLOT(-0.05,ATICK(L),TL,ARNG,0.0,0.5,TLNGTH,2)
      CALL XYPLOT(0.0,ATICK(L),TL,ARNG,0.0,0.5,TLNGTH,2)
   15 CONTINUE
      CALL XYPLOT(0.0,A2,1.0,0.1,0.0,0.0,TLNGTH,2)
      CALL XYPLOT(1.0,A2.1.0,0.1,0.0,0.0,TLNGTH,2)
      DO 20 L=1,10
      CALL XYPLOT(TLNGTH,BTICK(L),TL,ARNG,0.0,0.5,TLNGTH,2)
      CALL XYPLOT(TL1,BTICK(L),TL,ARNG,0.0,0.5,TLNGTH,2)
      CALL XYPLOT(TLNGTH,BTICK(L),TL,ARNG,0.0,0.5,TLNGTH,2)
   20 CONTINUE
      CALL XYPLOT(1.0,A1,1.0,0.1,0.0,0.0,TLNGTH,2)
      CALL XYPLOT(0.0,A1,1.0,0.1,0.0,0.0,TLNGTH,2)
      RETURN
      END(1,0,0,0,0,0,1,0,0,0,0,0,0,0,0)
```

13. Subprogram TICKS

TICKS draws tick marks on the side of the box drawn by AXPLOT to mark 0.1, 0.05, 0.025, 0.0125, and 0.01 times the maximum value of r(t).

```
  TICKS   SUBROUTINE TO CALCULATE AMPLITUDE TICK MARKS

      SUBROUTINE TICKS
      DIMENSION T(2501),TAUP(101),TAUT(101),BP(101),BT(101),EO(2501,2),
     1PKMAG(2000,2),PKTIM(2000,2),PKRAT(2000),ATICK(20),BTICK(20)
      COMMON TMAXI,TINC,TR,TLNGTH,TRNGE,TLAG,LASTT,ITI2,ITM1,ITM2,
     1ITM1M1,ITM2P1,N1,N2,NINC,NPK,NPK1,NPK2,PKMAX1,PKMAX2,PKTIM1,
     2PKTIM2,IPERM,ITEMP,J1,IFLAG,AMPRNG,A1,A2,ARNG10,RATIO1,SPKMAX,
     3TZERO,T,TAUP,TAUT,BP,BT,EO,PKMAG,PKTIM,PKRAT,ATICK,BTICK,TL,TL1
      ATICK(10)=0.1*PKMAX1
      ATICK(9)=0.05*PKMAX1
      ATICK(8)=0.025*PKMAX1
      ATICK(7)=0.0125*PKMAX1
      ATICK(6)=0.01*PKMAX1
      ATICK(5)=-ATICK(6)
      ATICK(4)=-ATICK(7)
      ATICK(3)=-ATICK(8)
      ATICK(2)=-ATICK(9)
      ATICK(1)=-ATICK(10)
      BTICK(1)=ATICK(10)
      BTICK(2)=ATICK(9)
      BTICK(3)=ATICK(8)
      BTICK(4)=ATICK(7)
      BTICK(5)=ATICK(6)
      BTICK(6)=ATICK(5)
      BTICK(7)=ATICK(4)
      BTICK(8)=ATICK(3)
      BTICK(9)=ATICK(2)
      BTICK(10)=ATICK(1)
      RETURN
      END(1,0,0,0,0,0,1,0,0,0,0,0,0,0,0)
```

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